UNCLASSIFIED

AD 273 717

reproduced

by the

ARMED SERVICES TECHNICAL INFORMATION AGENCY
ARLINGTON HALL STATION
ARLINGTON 12, VIRGINIA

UNCLASSIFIED

NAVWEPS REPORT 7735
Part 1
NOTS TP 2693
COPY 48

WATER-EXIT BEHAVIOR OF MISSILES

Part 1. Preliminary Studies

by

J. G. Waugh
and
G. W. Stubstad
Underwater Ordnance Department

N-62-5-6

ABSTRACT. Water-exit launchings were made with a 2-inch-diameter hemisphere-head missile at 60-fps nominal water-exit velocity; launching angles of 15, 30, and 90 degrees with respect to the horizontal; and different degrees of cavitation ranging from nearly fully wetted flow to completely enveloping cavitation. Perturbations in missile pitch at water exit increased with decrease in trajectory angle and the maximum perturbations occurred under conditions of fully developed cavitation. From the results it is inferred that water-exit perturbations will pose problems in service missile water-exit technology.

The addition of a nose probe to measure cavitating missile attitudes altered the water-exit perturbations and sometimes caused erratic cavities to form. An annular groove in the missile nose at the zone of cavity separation stabilized the cavity and allowed more consistent results to be obtained.

U.S. NAVAL ORDNANCE TEST STATION

China Lake, California

11 May 1961

U. S. NAVAL ORDNANCE TEST STATION

AN ACTIVITY OF THE BUREAU OF NAVAL WEAPONS

W. W. HOLLISTER, CAPT., USN
Commander

WM. B. McLEAN, PH.D.
Technical Director

FOREWORD

A knowledge of missile water-exit perturbations that may obtain under conditions of cavitation, and the validity of modeling parameters for modeling these perturbations, have recently assumed importance in practical application.

The data presented in this report indicate that a small-scale missile is subjected to significant perturbations at water exit under all conditions of cavitation and suggest that these perturbations will pose problems in service missile technology. These data may be used in the assessment of modeling parameters in further scaled studies with larger missiles.

The study was made under Bureau of Naval Weapons Task Assignment RRRE 07001/216-1/R009-01-001 during Fiscal Years 1960 - 1961.

The material presented here constitutes Part 1 of this report. Further investigations will be published as additional parts. Part 1 was reviewed by F. D. Donoghue of the Bureau of Naval Weapons and by H. R. Kelly and H. T. Yerby of this Station for technical adequacy.

D. J. WILCOX, Head
Underwater Ordnance
Department

Released under
the authority of:

WM. B. McLEAN
Technical Director

NOTS Technical Publication 2693
NAVWEPS Report 7735, Part 1

Published by . . . . . Underwater Ordnance Department
Manuscript 807/MS-135
Collation . . . . Cover, 27 leaves, abstract cards
First printing . . . . 115 numbered copies
Security classification . . . . UNCLASSIFIED

INTRODUCTION

A knowledge of the water-exit behavior of missiles and of problems associated with this behavior has recently assumed great importance in national defense, yet little is known about the subject (Ref. 1). Available data indicate that missile water-exit perturbations may take place under conditions of fully wetted flow, and tests with service missiles indicate that perturbations do take place under conditions of cavitation. However, very little data are available on missile water-exit perturbations that may obtain under varying degrees of cavitation--conditions that are likely to arise in practical applications, and they are inadequate for assessing the validity of the applicable modeling parameters.

From a structural-strength standpoint, the design of a missile and its internal components for water exit does not present the same problems as design for water entry, because the missile is emerging from one medium into another which is far more compressible and has much lower density and viscosity. Hence, instead of an increase there will be a more or less abrupt reduction of the forces that influence the missile in its water exit and subsequent air trajectory. For oblique water exit this reduction of forces would probably be asymmetrical and cause a refraction of the air trajectory and changes in the orientation and angular velocity of the missile. The problem is complex. The water-exit behavior of a missile will depend on many factors such as missile shape, ballistic parameters, velocity, trajectory angle, orientation, and the cavity bubble.

The missile water-exit studies reported here are preliminary and incomplete. They constitute the exploratory phase of a program whose purpose is twofold: (1) to determine whether missile water-exit perturbations under conditions of cavitation are sufficiently large to pose problems in missile water-exit technology, and (2) to provide data for a subsequent program to assess the validity of modeling parameters in modeling missile water-exit behavior under conditions of cavitation. In view of the present scarcity of such data, these preliminary data are of interest.

EXPERIMENTAL PROGRAM

MISSILE AND LAUNCHING FACILITIES

The missile used in these studies was launched with and without a nose probe. Its configuration with the probe is shown in Fig. 1, and its parameters are given in Table 1. The missile was made of black-

TABLE 1. Missile Parameters

Parameter	Dimension
Diameter, in	$2.000 \begin{smallmatrix} +0.000 \\ -0.001 \end{smallmatrix}$
Length,[a] in	12.004 ± 0.040
Mass, lb	1.323 - 1.329 for ML 7 to 22 1.272 - 1.283 for all others
Distance from CG to nose,[a] in	5.50 for all except: ML 7 to 22 . . . 5.60 ML 35 . . . . . 5.40 ML 69 . . . . . 5.48
Moment of inertia,[b] lb in^2 .	18.19 - 18.21 for all except ML 7 to 22, 35, 36, 38, 61 to 69, which were not recorded. They are believed to be close to the figures quoted above.

[a] Length of probe not included.
[b] About a transverse axis through the CG.

anodized Dural with longitudinal and transverse fiducial marks to facilitate reduction of the photographic data. The missile probe was made of cylindrical bronze welding rod lightly sprayed with black lacquer, and, unless otherwise stated, its leading end was carefully faced at right angles to its axis. The probe was mounted in the missile head, with deKhotinsky cement used to insure rigid binding so that the probe was accurately concentric with the missile axis. The probe was sufficiently rigid that it did not bend during underwater trajectory and water exit, but was pliable enough to deform without damage to the missile when the missile struck a nylon fabric backstop. A new probe was used for each launching. The other missile joints were sealed with dental wax to prevent water leakage into the missile.

The missile was launched under fresh water in the Variable-Angle Variable-Pressure Launching Tank (Fig. 2) in the Hydroballistics

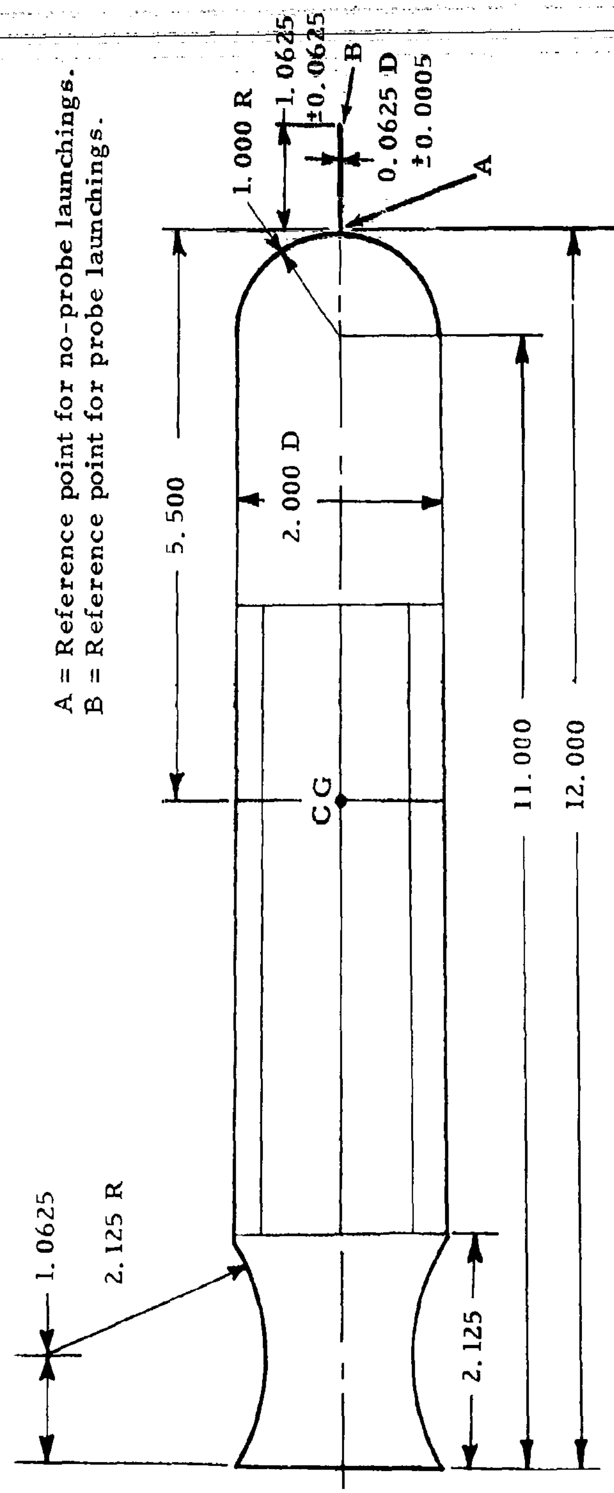


FIG. 1. Missile Configuration.

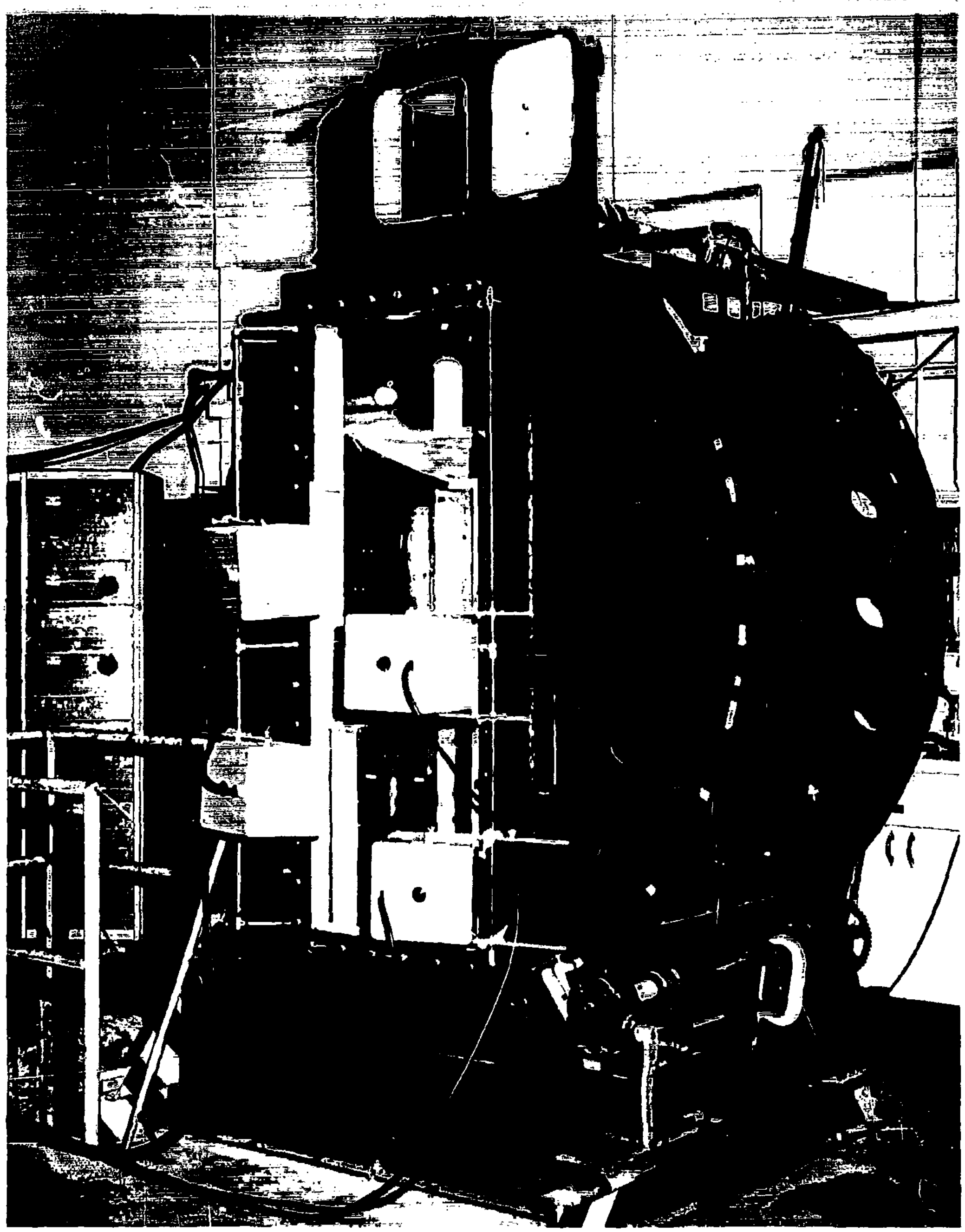


FIG. 2. Variable-Angle Variable-Pressure Launching Tank. Pit below tank provides space for launcher. Tank shown empty with backstop in position.

Laboratory, Naval Ordnance Test Station (NOTS), Pasadena, Calif. In this tank, missiles up to 2 inches in diameter can be launched under water with a maximum velocity of about 90 fps. The launching angle can be varied from 5 to 90 degrees with respect to the horizontal, and the gas pressure over the water surface can be varied from 1.5 to less than 0.1 atmosphere absolute. The launcher is mounted on the base of the tank and has an impelling piston extending into the tank through a water- and gas-tight seal. The piston is concentric with the center line of the tank and its motion is along the center line. A description of the tank (adapted for water-entry studies) is given in Ref. 2.

The launching system was designed to launch the missile with no angle of attack or pitch velocity and to minimize water flow due to launcher action. The missile was held in a ventilated sleeve-type carriage mounted on the end of the launching piston. Upon actuation, the piston was impelled forward by a pneumatic system outside of, and sealed off from, the interior of the tank. After about 0.9 foot of forward accelerated motion, the carriage-piston system was brought to a stop in about 0.5 foot by a hydraulic buffering system and the momentum-propelled missile emerged from the carriage and continued on its underwater trajectory. The free-flight distance before water surface penetration was at least 1 foot (i.e., one missile length). The initial launching velocity was adjusted to give a nominal missile velocity of 60 fps just before water exit.

The action of the launcher did not introduce any air, hydraulic fluid, grease, or other extraneous substances into the water. The tank water as supplied from the high-pressure city mains was supersaturated with air. Rapid de-aeration was accomplished by bubbling air through it for at least one hour at 0.1 atmosphere. Consequently, the repeatable equilibrium condition existed during each launching; diffusion of air into the cavity was minimized; and water-vapor, or very nearly water-vapor, cavitation obtained. The degree of missile cavitation during the underwater trajectory and at water exit was adjusted by varying the air pressure over the water surface, i.e., varying the cavitation number. The air pressures used in these studies ranged from 0.1 to 1.0 atmosphere absolute.

In describing gas pressures and densities, it was found convenient to define reference standards. Since the average ambient conditions of temperature and pressure at the Morris Dam Torpedo Range (where prototype tests may be made) and the Hydroballistics Laboratory at NOTS approximated 20°C and 740 mm (29.14 inches) of mercury, 1 atmosphere was defined as 740 mm of mercury. Gas densities are described in terms of a gas-density coefficient, ρ', which is the ratio of the density of the gas at the temperature and pressure of the tank atmosphere to that of dry air at 20°C and 740-mm pressure.

Sideview water-exit data were obtained with a rotating-disk camera and Edgerton-type stroboscopic flash lamps adjusted to give 19 exposures at a frequency of 250 per second, i.e., a time interval of 4 milliseconds between frames. The range of missile positions over the exposure sequence was adjusted by means of a time-delay apparatus that triggered the flash lamps at an appropriate time after launcher actuation. Typical rotating-disk camera films are shown in Fig. 3, 4, and 5.

The fiducial marks for data reduction were fine white threads mounted on the outside surface of the tank window at the normal projection of the tank (and launcher) center line in the plane of the window, and at the intersection of the planes of the water surface and the window. Additional threads and black-and-white wedge-shaped tabs mounted on the window provided the zero points required for measurement and calculation of the data. The rotating-disk camera was positioned so that its axis was normal to the plane of the tank window and passed through the point of intersection of the threads representing the projected water surface and center line. The photographic data were reduced and plotted as functions of time from water exit. The time of water exit is defined as the instant at which the reference point on the missile nose intersects the plane of the undisturbed water surface (Fig. 1). Figure 6 presents data from a typical launching and shows the quality of the data obtained.

TEST CONDITIONS

In the selection of test conditions, certain assumptions and compromises had to be made. To begin with, the launching tank can accommodate models no larger than 2 inches in diameter, which is certainly small compared with present service missiles. Furthermore, in order to determine, on the basis of small model tests, whether significant service-missile water-exit perturbations would obtain, it is necessary to assume, a priori, that one-to-one Froude and cavitation-number scaling will be valid for modeling service-missile behavior if Reynolds-number effects can be ignored. This assumption seems reasonable but still has to be demonstrated. The validity of one-to-one Froude and cavitation-number scaling for modeling missile water-exit behavior under conditions of cavitation will be investigated in a later program.

In order that the effects of non-modeling of the Reynolds number be minimized without artificial turbulence stimulation, it is necessary that both model and prototype underwater velocities be sufficiently high that the Reynolds number for both will correspond to transition from laminar to turbulent flow close to the nose. For prototype (service) missiles this restriction would offer no problem, but for a 2-inch-diameter hemisphere-head missile, the critical Reynolds number would probably correspond to a missile velocity somewhat below 60 fps (Ref. 3). Therefore the velocity of the missile should be not less than 60 fps. On

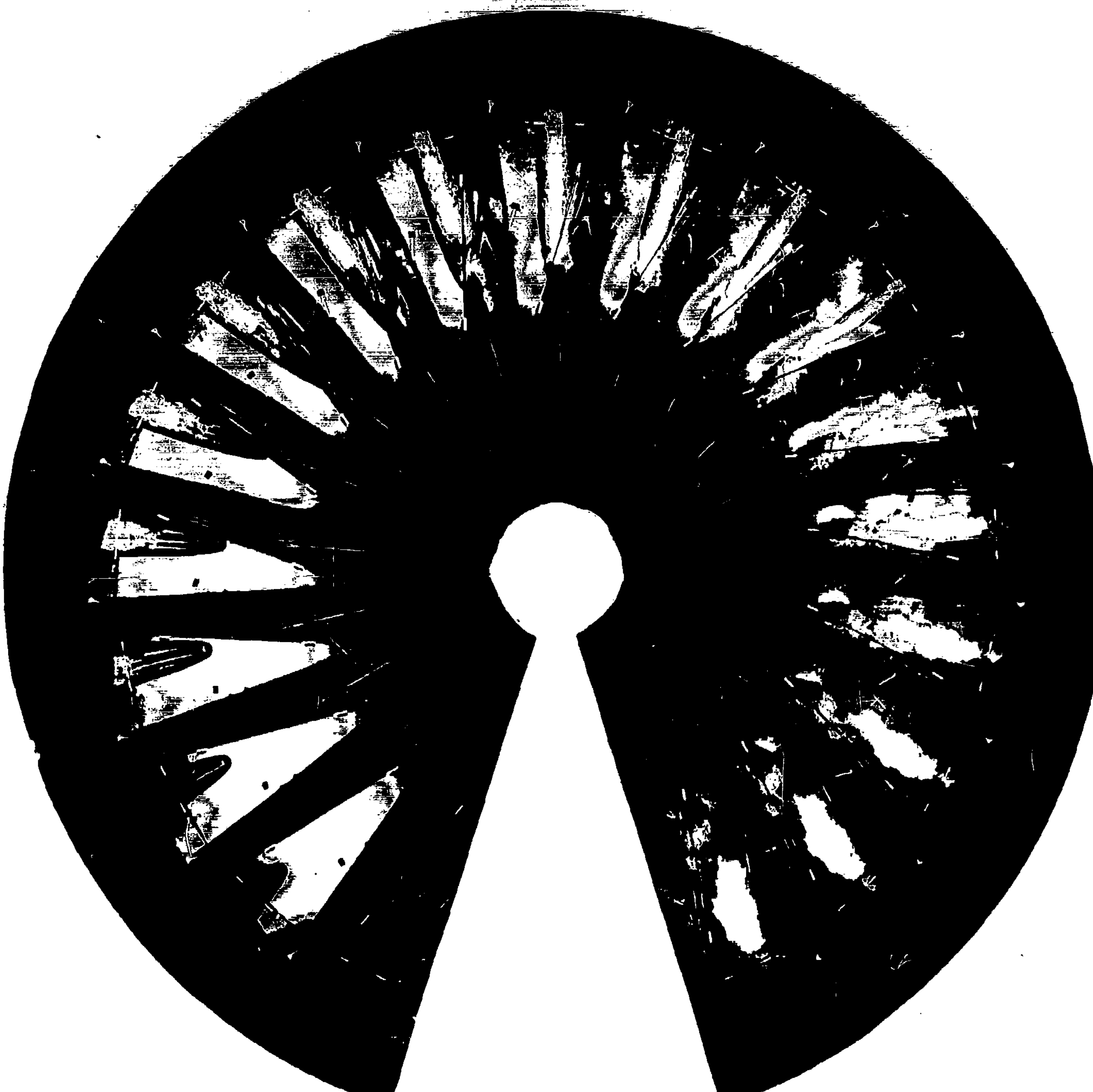


FIG. 3. Water Exit of Missile Without Probe Launched at 15-deg Angle. Velocity at water exit, 56.7 fps; pressure, 0.1 atm.

FIG. 4. Water Exit of Missile Without Probe Launched at 30-deg Angle. Velocity at water exit, 58.7 fps; pressure, 0.1 atm.

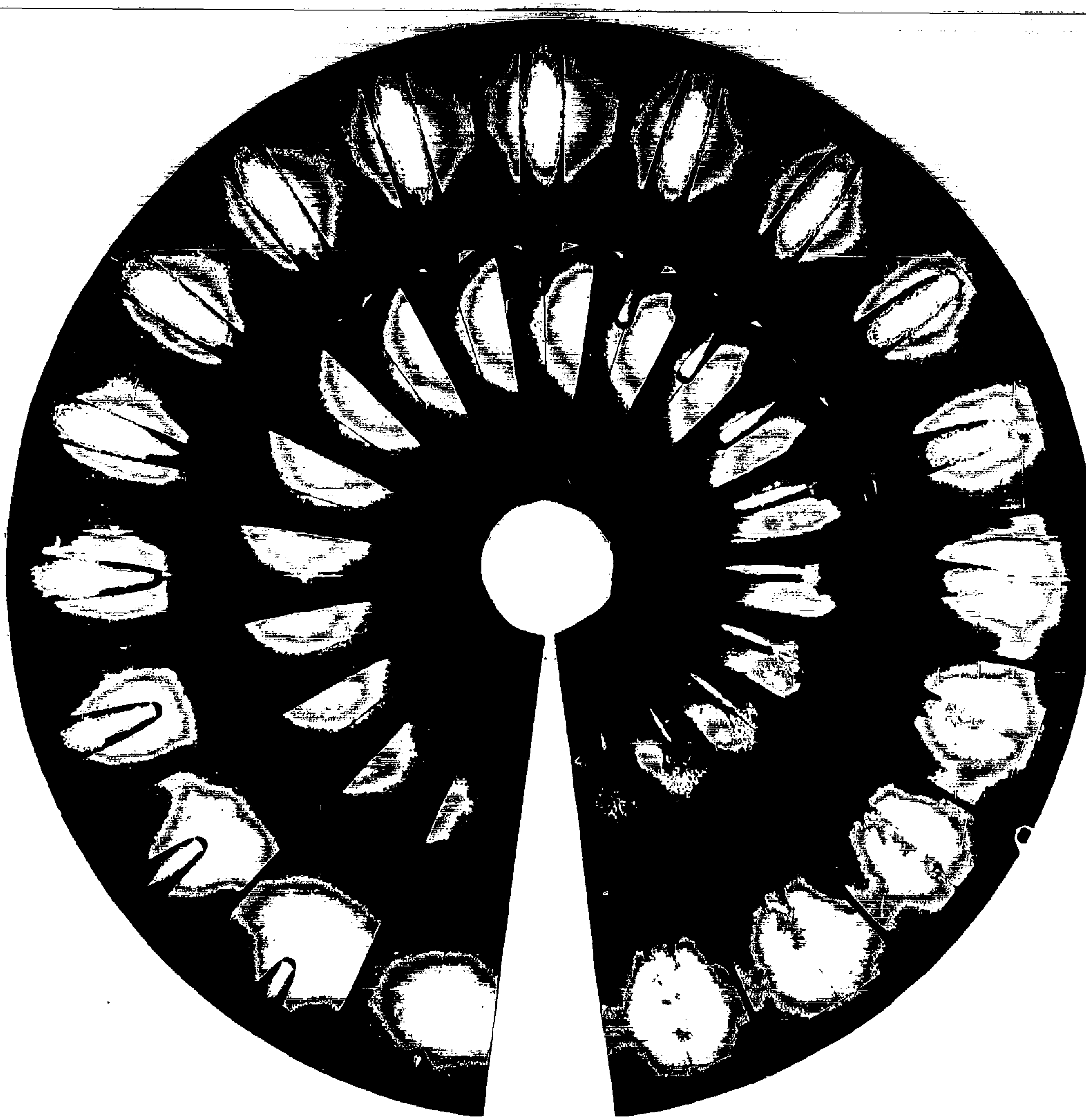


FIG. 5. Water Exit of Missile Without Probe Launched Vertically. Velocity at water exit, 55.7 fps; pressure, 0.1 atm.

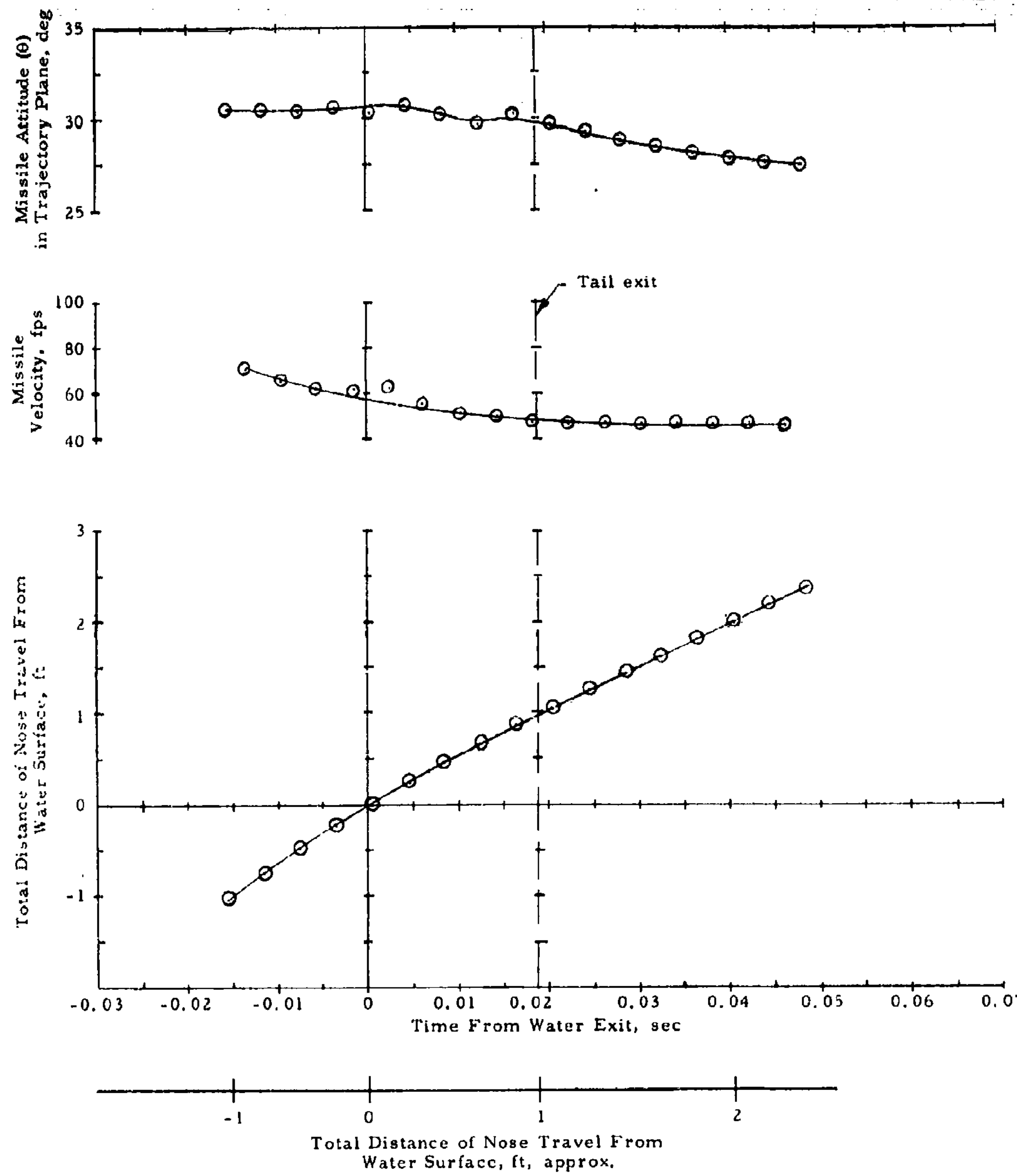


FIG. 6. Time Curves for an Individual Launching.

the basis of Froude scaling, 60-fps water-exit velocity would correspond to 190 fps for a 20-inch-diameter prototype and more for larger missiles. This is quite high in terms of present service-missile velocities, but it is believed that the future trend will be toward increased water-exit velocity. It is also believed that at lower water-exit velocities, missile water-exit perturbations tend to increase. Therefore, if significant perturbations are observed at the water-exit velocities reported here, they are also likely to occur at lower velocities.

It was realized that fully wetted or slightly cavitating flow would not offer any problem in obtaining underwater photographic data, but the opacity and/or optical distortion of the cavity would prevent obtaining such data from fiducial marks on the missile itself. Additional difficulties would be introduced by obscuration due to the envelope of water around the missile and the splash as the missile passes through the water-air interface.

The use of a probe on the missile nose as shown in Fig. 1 would solve the problem of obtaining data on missile position and attitude, but it would have the disadvantages of making the missile nose atypical from service-missile nose configurations and the hemisphere-head configuration less tractable for water-exit theory studies. In consequence, two series of water-exit studies were planned. The first series would be conducted without a probe to investigate the water-exit perturbations that might obtain with the typical and theoretically tractable hemisphere head. The second series would be conducted with a probe to (1) obtain more accurate and reliable data on missile water-exit behavior, (2) determine whether the probe caused significant deviations in missile behavior, and (3) further develop the probe technique for future water-exit studies.

DISCUSSION OF RESULTS

WATER-EXIT BEHAVIOR

A total of 71 launchings was made at trajectory angles of 15, 30, and 90 degrees with respect to the horizontal and at various atmospheric pressures over the water surface. The 15- and 30-degree conditions were investigated both with and without the probe, and the 90-degree condition without the probe. Launching conditions are listed in Tables 2 - 6. At least two launchings were made at each different condition. The water-exit velocities obtained during the 90-degree launchings at air pressures above 0.2 atmosphere fell significantly below the desired 60 fps. This was caused by an increase in the underwater drag as the missile became more fully wetted (Fig. 7). As a result, higher launching velocities were used for the subsequent 15- and 30-degree launchings.

TABLE 2. Water-Exit Launching Data

Hemisphere head missile without probe. Trajectory launching angle: 15 degrees.

ML No.	Air Pressure in Tank, atm	Initial Attitude, deg[a]	v_e, fps	F	σ	ρ'	τ
77	1.00	15.3	55.0	23.7	0.685	0.99	443.0
78	1.00	14.7	54.0	23.4	0.706	0.99	436.6
79	0.75	13.8	54.3	23.4	0.527	0.75	437.4
80	0.75	14.5	56.5	24.4	0.487	0.75	455.1
81	0.51	14.8	56.2	24.3	0.330	0.50	452.5
82	0.51	15.2	54.5	23.5	0.351	0.50	438.8
182	0.30	15.0	61.5	26.5	0.158	0.30	496.5
186	0.30	15.0	61.6	26.6	0.157	0.30	497.4
83	0.20	15.8	60.0	25.9	0.107	0.20	483.1
84	0.20	16.3	58.6	25.3	0.113	0.20	471.8
87	0.10	15.8	58.5	25.3	0.049	0.10	471.0
88	0.10	16.2	56.7	24.5	0.052	0.10	456.5

[a] Attitude of missile measured when foremost point of missile nose is 6 in. from the point of surface penetration.

TABLE 3. Water-Exit Launching Data

Hemisphere head missile with probe. Trajectory launching angle: 15 degrees.

ML No.	Air Pressure in Tank, atm	Initial Attitude, deg[a]	v_e, fps	F	σ	ρ'	τ
89	1.00	15.2	58.0	25.0	0.616	0.98	468.3
90	1.00	15.4	58.9	25.4	0.597	0.98	475.6
91	0.75	15.0	63.0	27.2	0.388	0.73	509.6
92	0.75	14.6	57.6	24.9	0.464	0.73	465.9
93	0.51	15.0	56.1	24.2	0.327	0.50	453.6
94	0.51	15.2	61.9	26.7	0.268	0.50	500.5
122	0.41	15.2	58.7	25.4	0.237	0.40	474.1
123	0.41	15.2	58.1	25.1	0.243	0.40	468.4
118	0.30	15.4	62.6	27.0	0.153	0.30	504.6
119	0.30	15.4	59.5	25.7	0.170	0.30	479.6
95	0.20	15.2	59.0	25.5	0.106	0.20	477.1
96	0.20	15.9	66.2	28.6	0.084	0.20	535.3
97	0.10	16.2	63.3	27.3	0.038	0.10	511.8
98	0.10	15.3	58.1	25.1	0.045	0.10	469.8

[a] Attitude of missile measured when foremost point of missile nose is 6 in. from the point of surface penetration.

TABLE 4. Water-Exit Launching Data

Hemisphere head missile without probe. Trajectory launching angle: 30 degrees.

ML No.	Air Pressure in Tank, atm	Initial Attitude, deg[a]	V_e, fps	F	σ	ρ'	τ
60	1.00	29.9	57.5	24.8	0.632	1.00	462.5
69	1.00	30.5	57.2	24.7	0.637	0.99	460.4
70	1.00	29.6	58.5	25.3	0.609	1.00	470.8
73	1.00	29.8	56.0	22.4	0.663	0.99	450.9
74	1.00	29.4	56.1	24.2	0.660	0.99	451.7
67	0.75	30.2	58.0	25.0	0.463	0.75	466.3
68	0.75	30.0	57.3	24.7	0.475	0.75	460.7
61	0.51	30.1	60.5	26.1	0.286	0.51	486.7
66	0.51	30.2	58.2	25.1	0.309	0.51	467.9
64	0.20	30.0	59.9	25.9	0.109	0.20	481.6
65	0.20	30.0	60.4	26.1	0.107	0.20	485.6
62	0.10	30.0	58.0	25.0	0.050	0.10	466.6
63	0.10	30.0	58.0	25.0	0.051	0.10	466.3
71	0.10	30.0	58.7	25.3	0.049	0.10	472.4

[a] Attitude of missile measured when foremost point of missile nose is 6 in. from the point of surface penetration.

TABLE 5. Water-Exit Launching Data

Hemisphere head missile with probe. Trajectory launching angle: 30 degrees.

ML No.	Air Pressure in Tank, atm	Initial Attitude, deg[a]	V_e, fps	F	σ	ρ'	τ
100	1.00	30.2	58.7	25.3	0.602	0.99	473.8
101	1.00	30.2	55.2	23.8	0.681	0.99	445.5
104	0.75	30.2	61.6	26.6	0.406	0.73	497.9
105	0.75	30.2	59.2	25.6	0.440	0.73	478.5
102	0.50	30.0	63.5	27.4	0.257	0.51	512.5
103	0.50	30.0	65.5	28.3	0.241	0.51	528.6
106	0.41	29.8	58.2	25.1	0.239	0.40	470.4
107	0.41	30.0	58.3	25.2	0.239	0.40	471.2
108	0.30	30.0	60.2	26.0	0.163	0.30	486.5
109	0.30	30.0	60.6	26.2	0.161	0.30	489.8
110	0.20	30.2	59.3	25.6	0.105	0.20	479.4
111	0.20	30.0	58.3	25.2	0.108	0.20	471.3
116	0.10	29.8	54.7	23.6	0.055	0.10	440.6
117	0.10	29.8	57.2	24.7	0.051	0.10	460.8

[a] Attitude of missile measured when foremost point of missile nose is 6 in. from the point of surface penetration.

TABLE 6. Water-Exit Launching Data

Hemisphere head missile without probe. Trajectory launching angle: 90 degrees.

ML No.	Air Pressure in Tank, atm	Initial Attitude, deg[a]	v_e, fps	F	σ	ρ'	τ
9	1.01	90.0	44.2	19.1	1.076	1.01	355.3
12	1.00	90.0	42.2	18.2	1.169	1.00	339.1
13	1.00	90.0	44.0	19.0	1.076	1.00	353.6
17	0.75	90.0	45.0	19.4	0.769	0.75	362.1
18	0.75	90.0	44.0	19.0	0.804	0.75	354.1
19	0.75	90.0	45.0	19.4	0.769	0.75	362.1
8	0.52	90.0	47.8	20.6	0.466	0.52	384.3
11	0.50	90.0	46.0	19.9	0.485	0.50	369.8
14	0.50	90.0	46.2	19.9	0.480	0.50	371.3
7	0.21	90.0	56.2	24.3	0.129	0.21	451.8
15	0.20	90.0	55.0	23.6	0.128	0.20	442.6
16	0.20	90.0	54.3	23.4	0.132	0.20	437.0
10	0.09	90.0	57.8	25.0	0.045	0.09	464.7
20	0.12	90.0	56.8	24.5	0.063	0.12	457.1
21	0.12	90.0	55.5	24.0	0.066	0.12	447.9
22	0.12	90.0	57.5	24.8	0.065	0.12	460.6
35	0.09	90.0[b]	..	..	...	..	...
36	0.09	90.0[b]	..	..	...	..	...
38	0.09	90.0[b]	..	..	...	..	...

[a] Attitude of missile measured when foremost point of missile nose is 6 in. from the point of surface penetration.
[b] Used for calibration and attitude analysis.

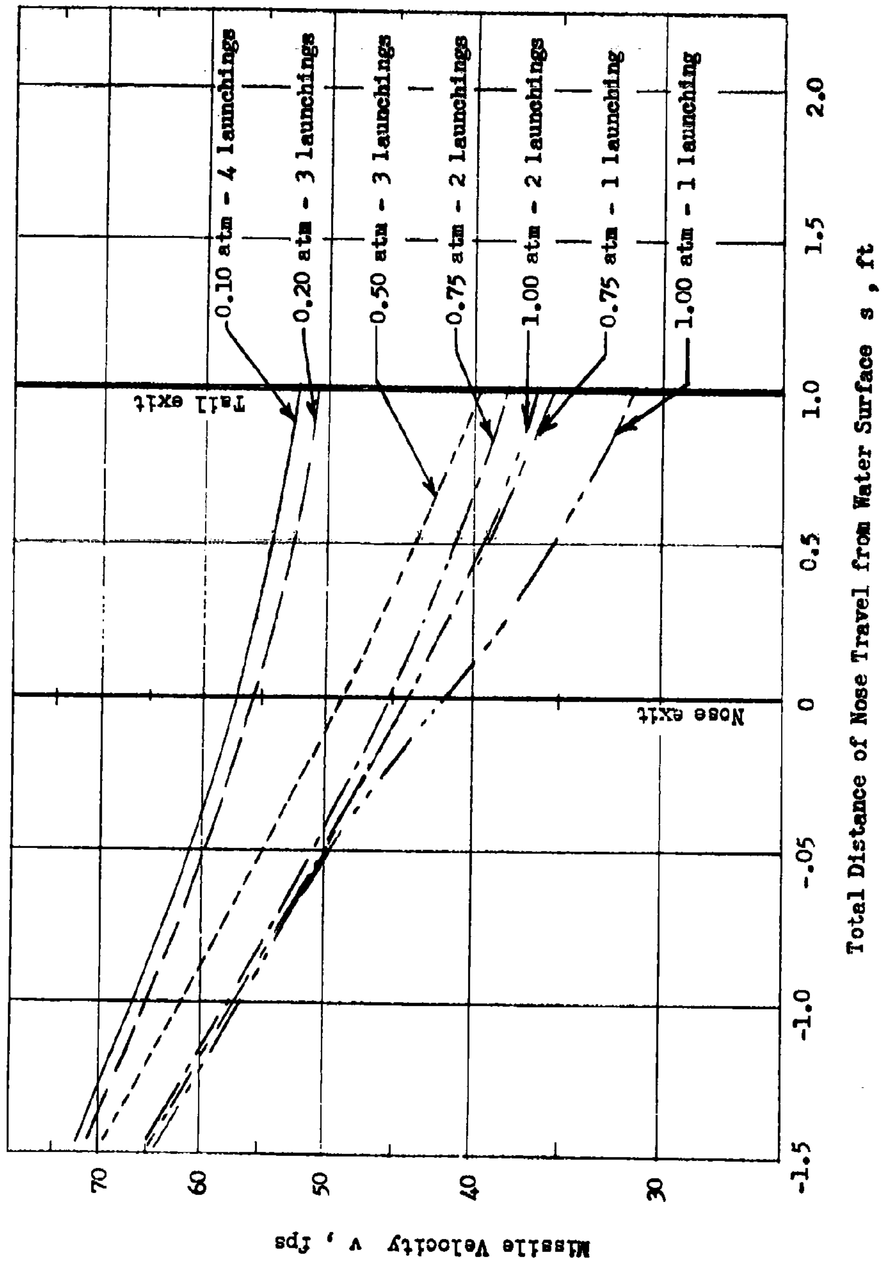


FIG. 7. Variation of Water-Exit Velocity With Atmospheric Pressure for 90-deg Launchings.

Figures 8 to 12 are composite photographs including selected frames from a launching at each test condition. The perturbation of the missile flight at water exit shows clearly in these pictures, the perturbation being dependent upon both underwater trajectory angle and atmospheric pressure above the water surface (i. e., degree of cavitation). The perturbation appears also to be influenced by the behavior of the cavity immediately prior to and during water exit. Thus the cavity may provide a means of controlling the water-exit perturbation.

Figures 13 to 17 show missile attitude, velocity, and distance traveled as functions of time at trajectory angles of 15, 30, and 90 degrees. It should be noted that the attitude curves for Fig. 17 are plotted on a larger scale than those of the other figures.

Addition of the probe to the missile nose caused an erratic cavity to form during some of the launchings (Fig. 18), and altered the water-exit behavior of the missile (Fig. 19 and 20). This erratic cavity behavior seemed to be correlated with deviation of the cavity separation zone from its normal position. In general, it can be said that if an erratic cavity was formed, the water-exit perturbation was amplified. If a normal cavity occurred, the water-exit perturbation appeared to be slightly suppressed by the presence of the probe.

As might be expected, the missile attitude is the parameter most sensitive to water-exit perturbations. Figures 21 to 23 show missile attitude at tail exit as a function of air pressure over the water surface. Data from each trajectory angle for probe and no-probe missiles are presented in a single curve. At trajectory angles of 15 and 30 degrees the maximum perturbation occurred at pressures of 0. 1 and 0. 2 atmosphere where the missile was in a fully developed cavity at the time of water exit. At 15 degrees the maximum perturbation occurred during launchings of the probe-nose missile; at 30 degrees the maximum perturbation occurred without the probe. For both trajectory angles the maximum perturbation was nose-up with respect to the underwater trajectory. Nose-down perturbations tended to occur under conditions of more fully wetted flow. For vertical water exit (90 degrees) there did not seem to be a trend in perturbation at any atmospheric pressure. The observed scatter in missile attitude was significantly less at 0. 1 atmosphere, indicating more stability under fully developed cavitation. At 0. 2 atmosphere the perturbation was still small at the time of tail exit but became larger during subsequent air flight (Fig. 17), suggesting that further random perturbations were caused by splash from the collapsing cavity. Some of the scatter at the higher air pressures may have been caused by transition from turbulent to laminar flow because the water-exit velocities were undesirably low at these pressures.

A numerical prediction of prototype behavior cannot be made from these data because the validity of Froude and cavitation-number scaling has not been established, and other factors which may be important in

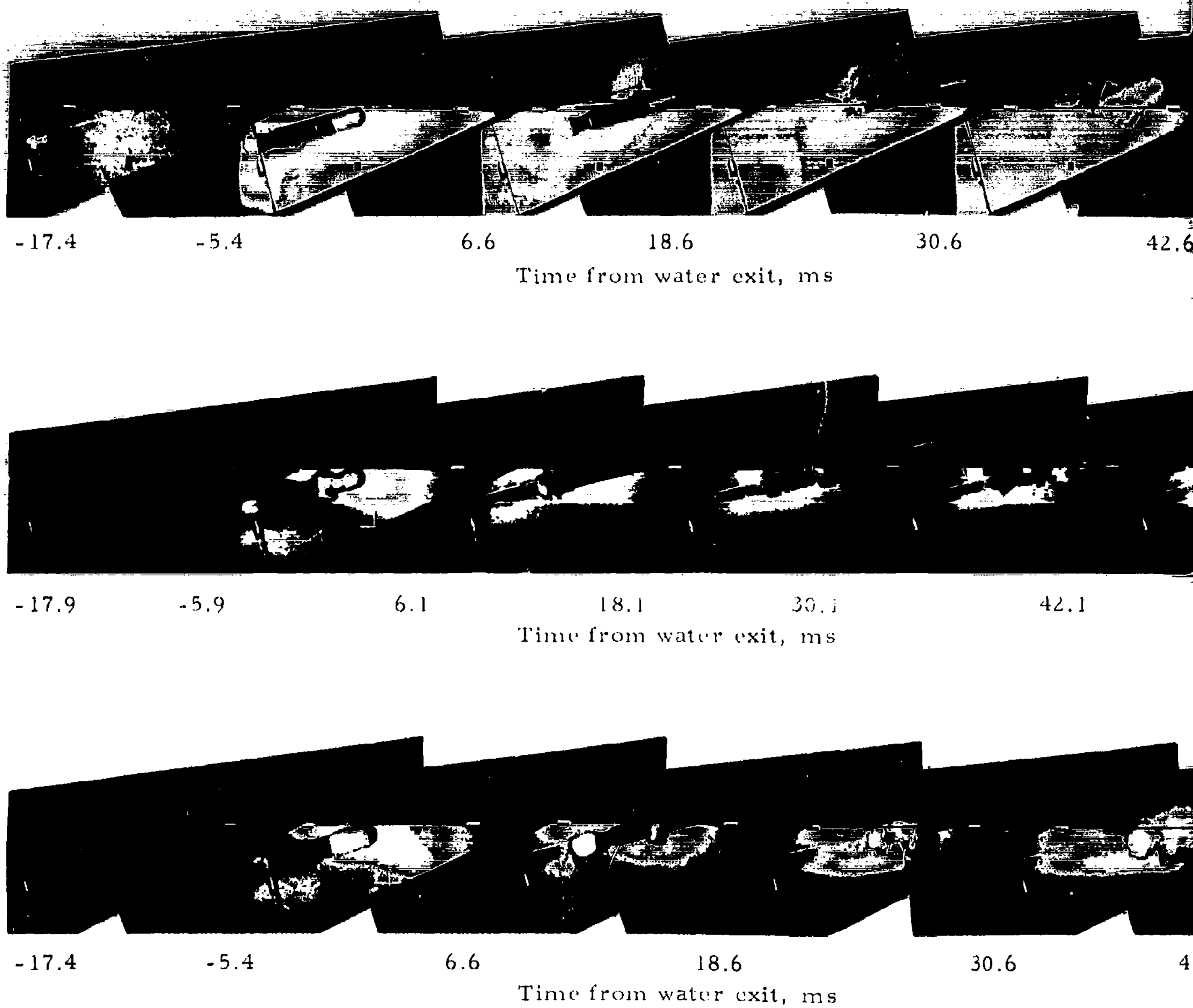


FIG. 8. Water Exit of Missile Without Probe Launched at 15-deg Angle. Nomin

1

(a) 1 atm pressure in tank

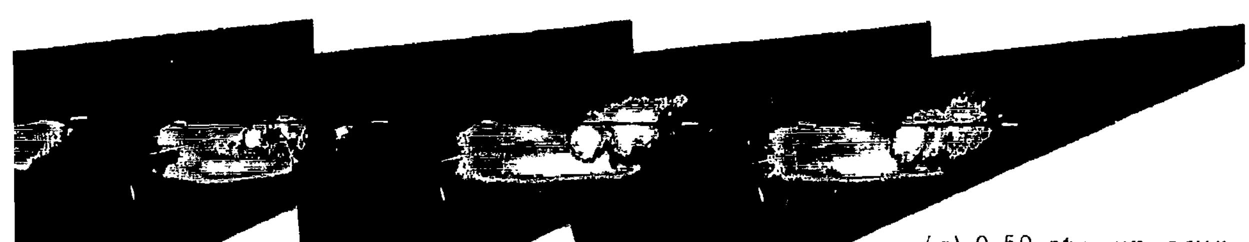
.6 30.6 42.6

ater exit, ms

(b) 0.75 atm pressure in tank

30.1 42.1

ater exit, ms



(c) 0.50 atm pressure in tank

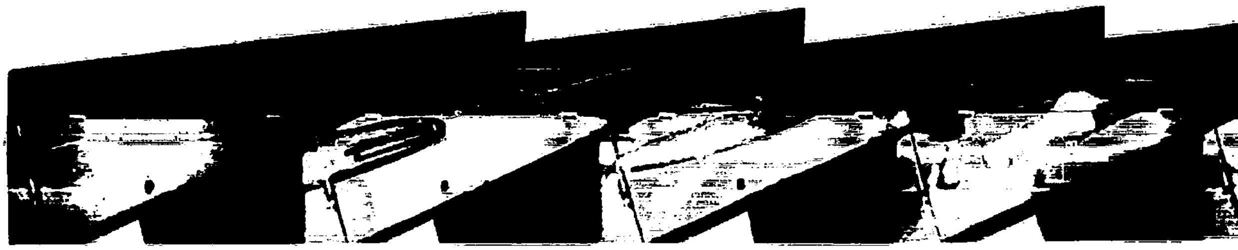
18.6 30.6 42.6

ater exit, ms

t Probe Launched at 15-deg Angle. Nominal water-exit velocity 60 fps.

-13.8 -1.8 10.2 22.2 34.2

Time from water exit, ms



-17.1 -5.1 6.9 18.9 30.9

Time from water exit, ms

-18.6 -6.6 5.4 17.4

Time from water exit, ms

FIG. 8. (Con

1

(d) 0.30 atm pressure in tank

34.2 46.2

m water exit, ms

(e) 0.20 atm pressure in tank

9 30.9 42.9

om water exit, ms

(f) 0.10 atm pressure in tank

17.4 29.4 41.4

om water exit, ms

FIG. 8. (Contd.)

2

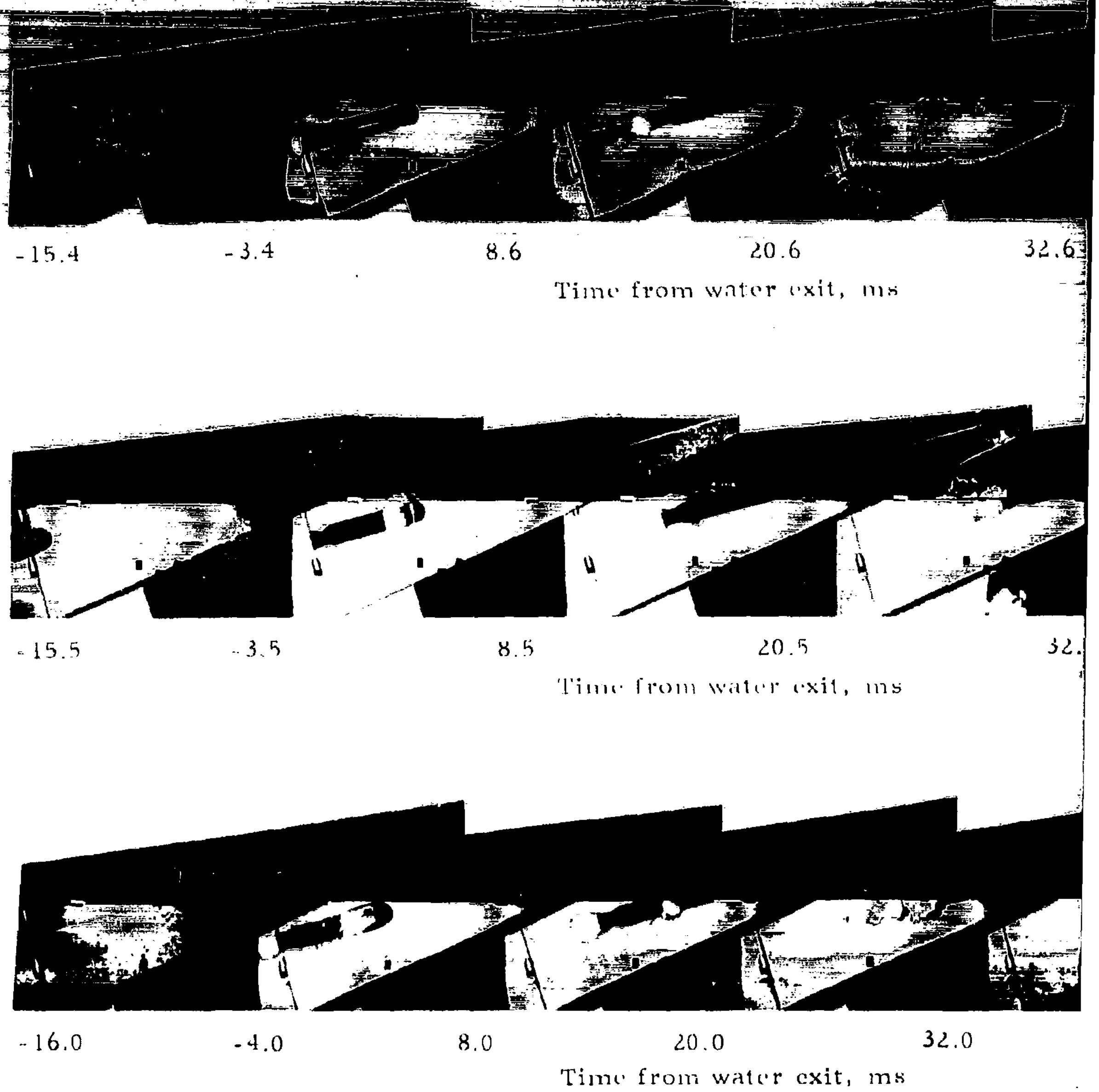
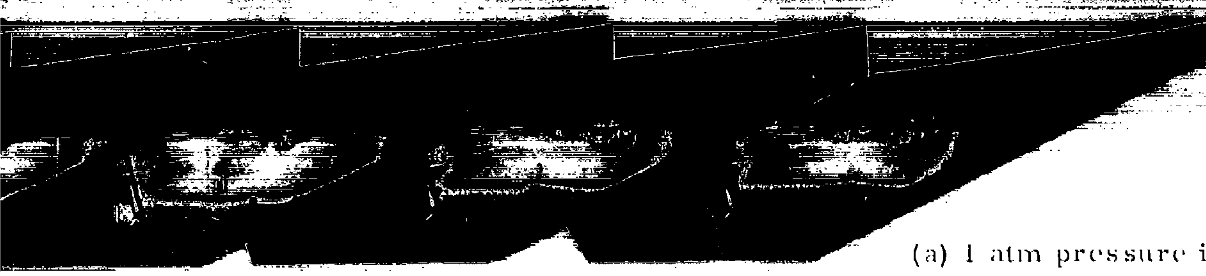


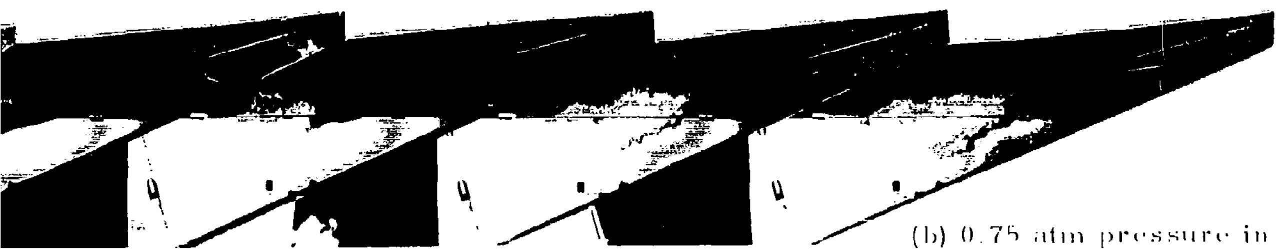
FIG. 9. Water Exit of Missile With Probe Launched at 15-de



(a) 1 atm pressure in tank

20.6 32.6 44.6

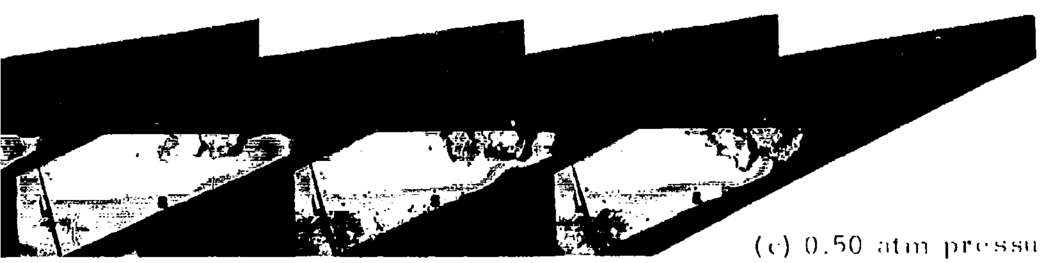
ater exit, ms



(b) 0.75 atm pressure in tank

20.5 32.5 44.5

ater exit, ms



(c) 0.50 atm pressure in tank

32.0 44.0

ater exit, ms

h Probe Launched at 15-deg Angle. Nominal water-exit velocity 60 fps.

2

-14.5 -2.5 9.5 21.5 33.5

Time from water exit, ms

-13.5 -1.5 10.5 22.5 34.5

Time from water exit, ms

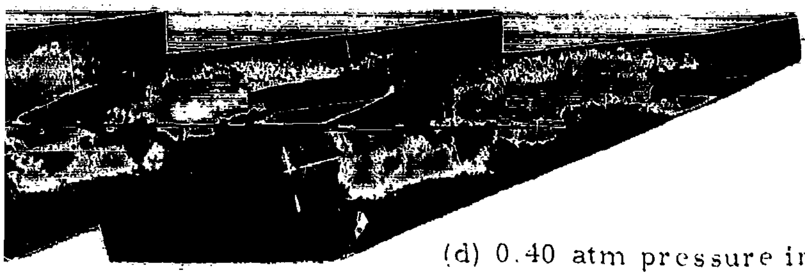
-16.4 -4.4 7.6 19.6

Time from water exit, ms

-17.5 -5.5 6.5 18.5

Time from water exit, ms

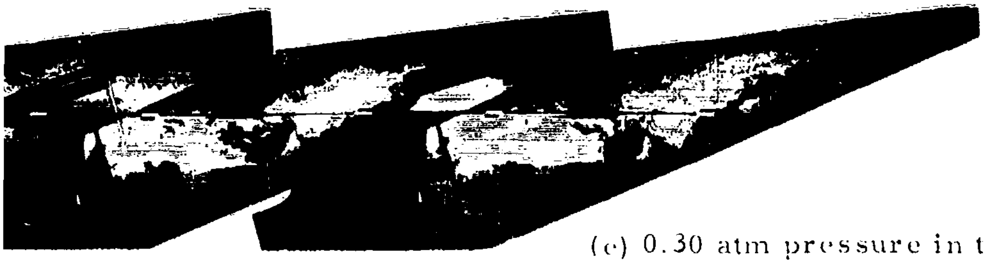
FIG. 9. (Cont



(d) 0.40 atm pressure in tank

45.5

2

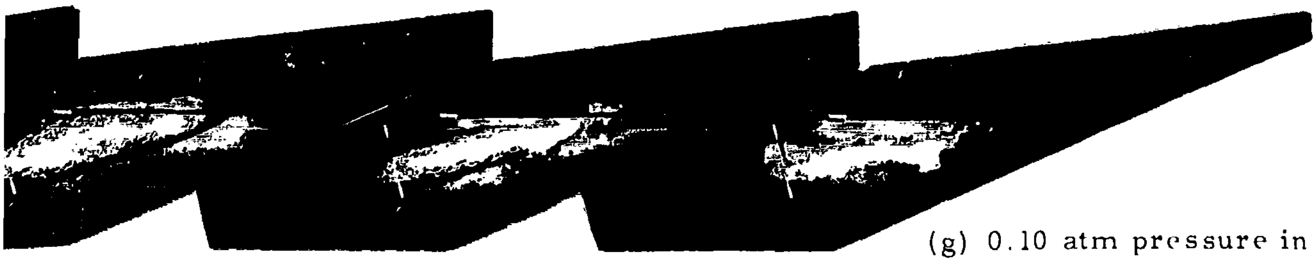


(e) 0.30 atm pressure in tank

.5 46.5

(f) 0.20 atm pressure in tank

31.6 43.6



(g) 0.10 atm pressure in tank

30.5 42.5

G. 9. (Contd.)

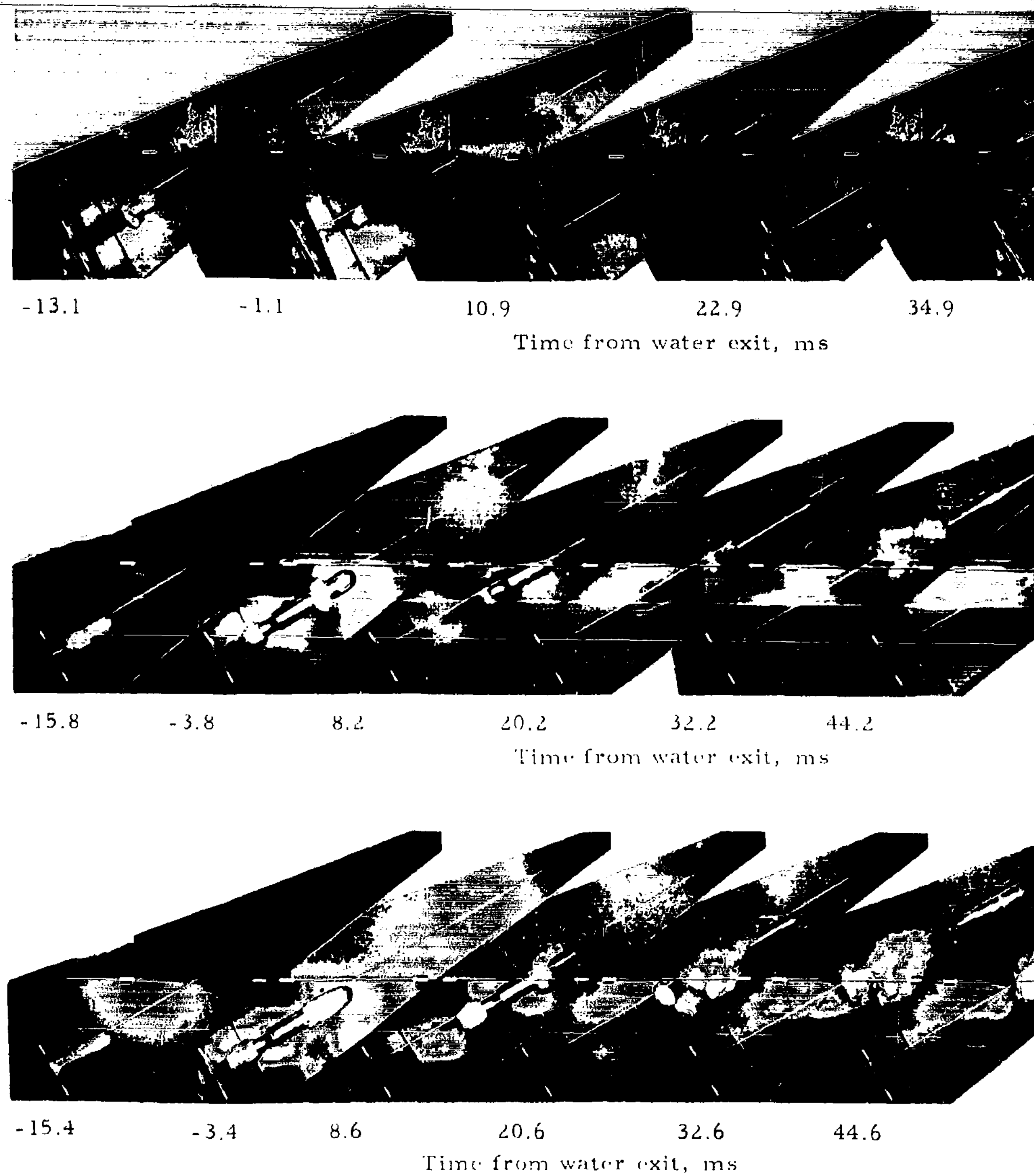
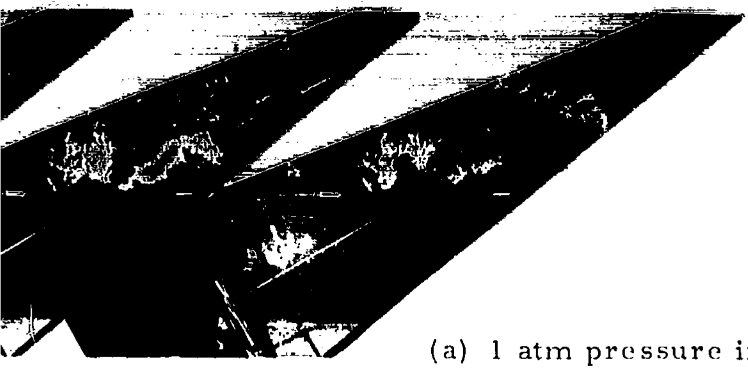


FIG. 10. Water Exit of Missile Without Probe Launched at 30-deg Angle



(a) 1 atm pressure in tank

46.9

) 0.75 atm pressure in tank

0.50 atm pressure in tank

2

Nominal water-exit velocity 60 fps.

-14.4 -2.0 10.0 22.0 34.0 46.0

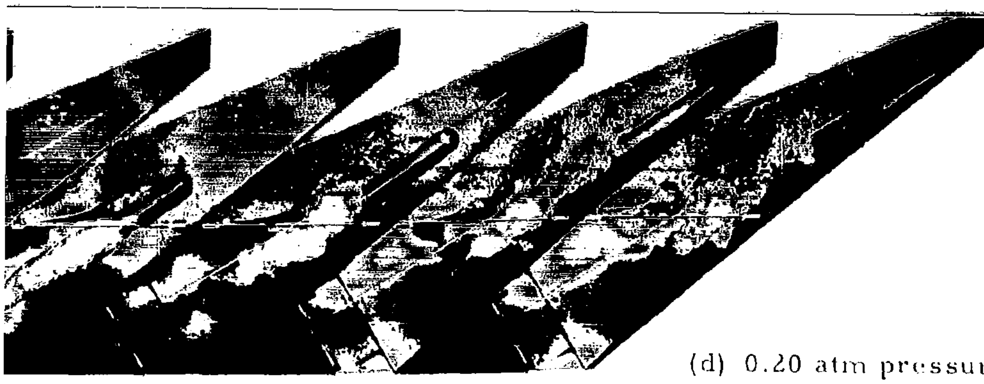
Time from water exit, ms

-14.2 -2.2 9.8 21.8 33.8

Time from water exit, ms

FIG. 10. (Contd.)

1



(d) 0.20 atm pressure in tank

22.0 34.0 46.0

Time from water exit, ms

(e) 0.10 atm pressure in tank

9.8 21.8 33.8 45.8

Time from water exit, ms

FIG. 10. (Contd.)

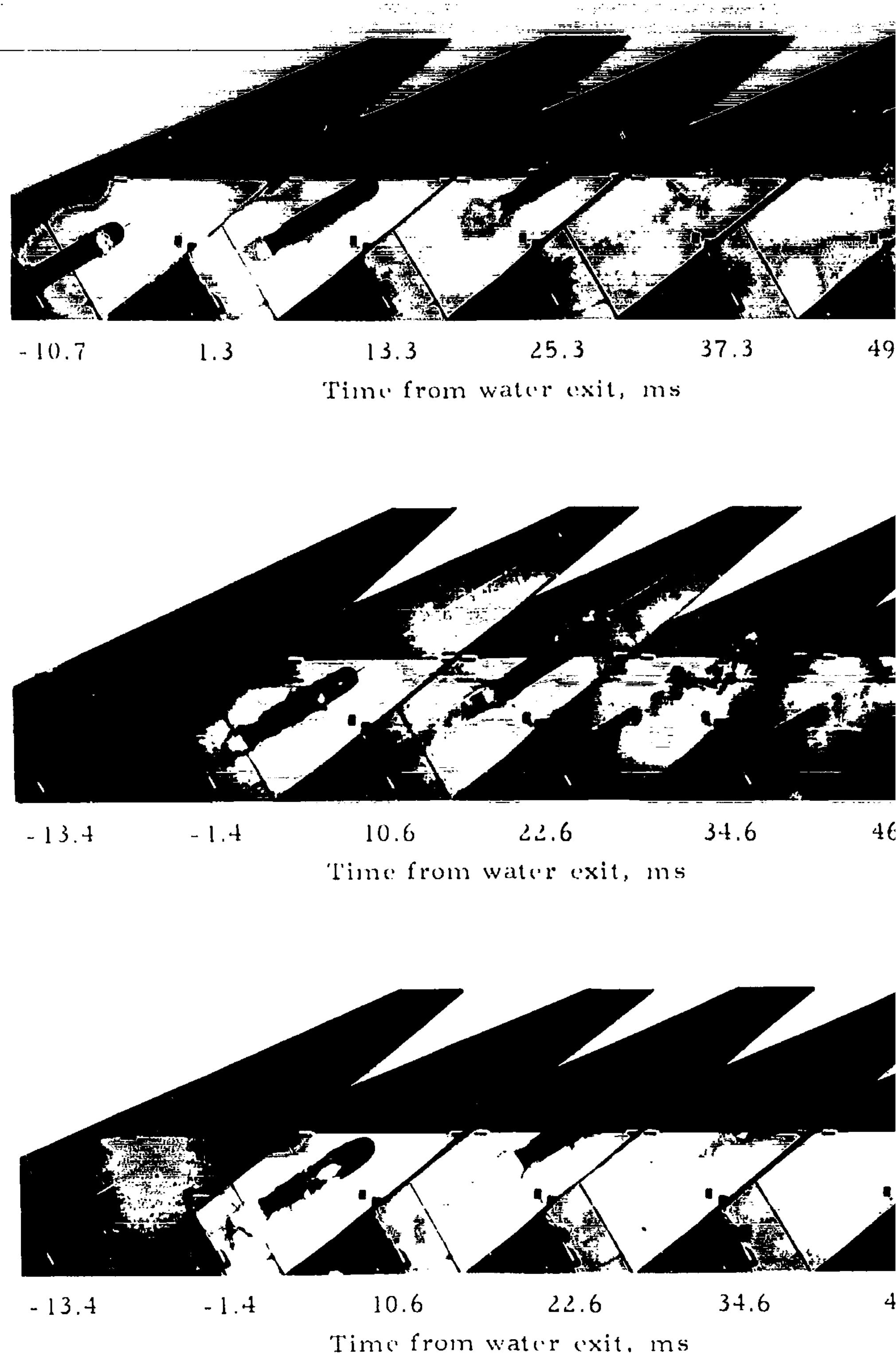
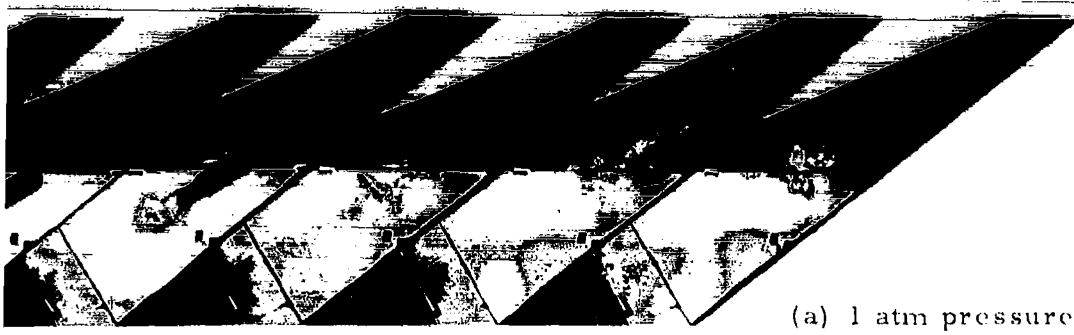


FIG. 11. Water Exit of Missile With Probe Launched at 30-deg



(a) 1 atm pressure in tank

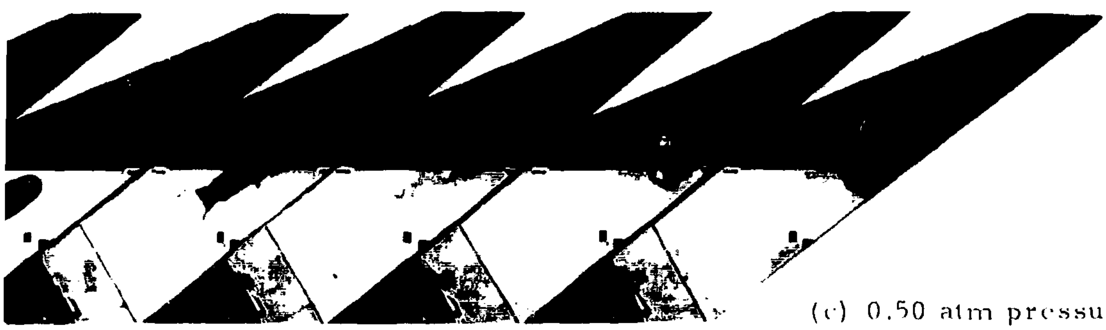
13.3 25.3 37.3 49.3

ime from water exit, ms

(b) 0.75 atm pressure in tank

10.6 22.6 34.6 46.6

'ime from water exit, ms



2

(c) 0.50 atm pressure in tank

10.6 22.6 34.6 46.6

'ime from water exit, ms

Missile With Probe Launched at 30-deg Angle. Nominal water-exit velocity 60 fps.

-11.4 0.6 12.6 24.6 36.6 48.6

Time from water exit, ms

(d) 0.40 atm pressure in tank

-12.2 -0.2

-12.3 -0.3 11.7 23.7 35.7 47.7

Time from water exit, ms

(f) 0.20 atm pressure in tank

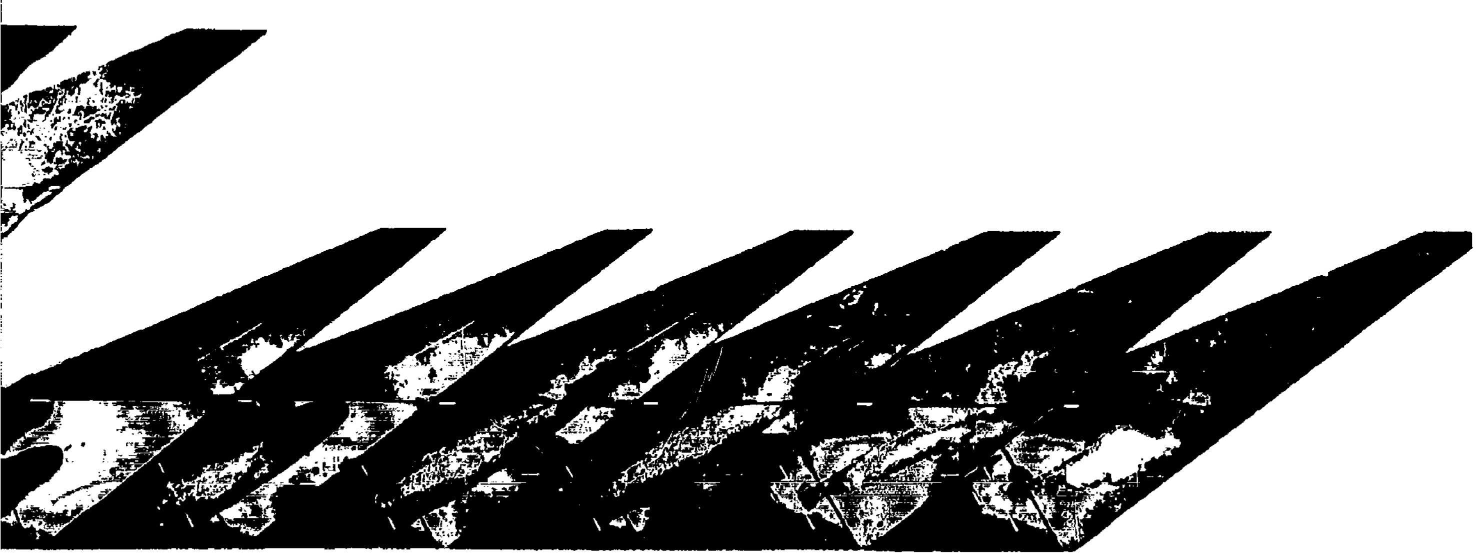
-10.7 1.3

FIG. 11. (C

-12.2 -0.2 11.8 23.8 35.8 47.8

Time from water exit, ms

(e) 0.30 atm pressure in tank



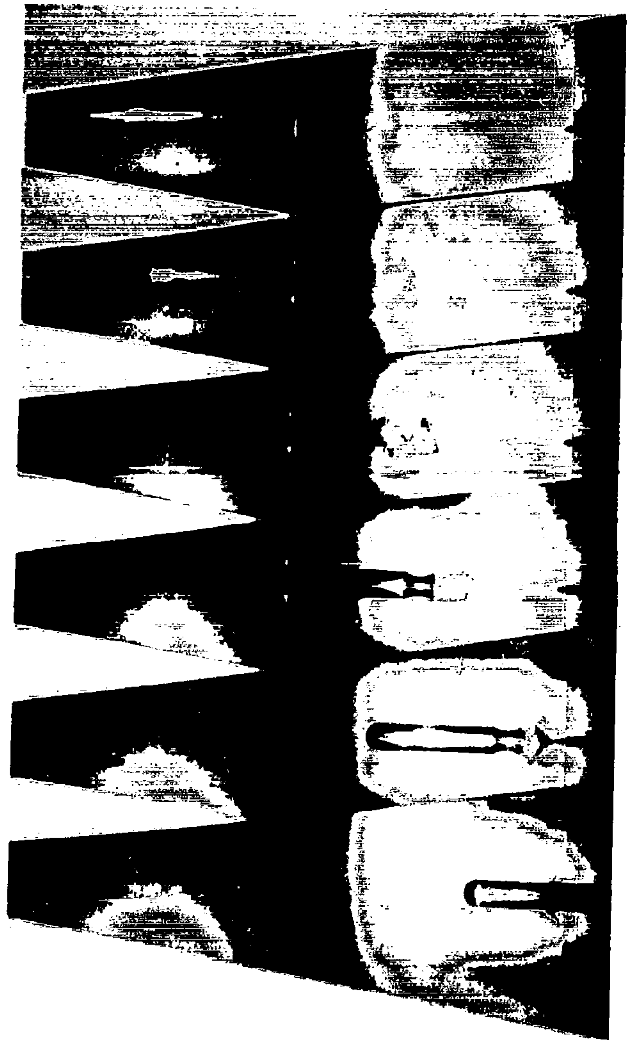
.7 1.3 13.3 25.3 37.3 49.3

Time from water exit, ms

(g) 0.10 atm pressure in tank

FIG. 11. (Contd.)

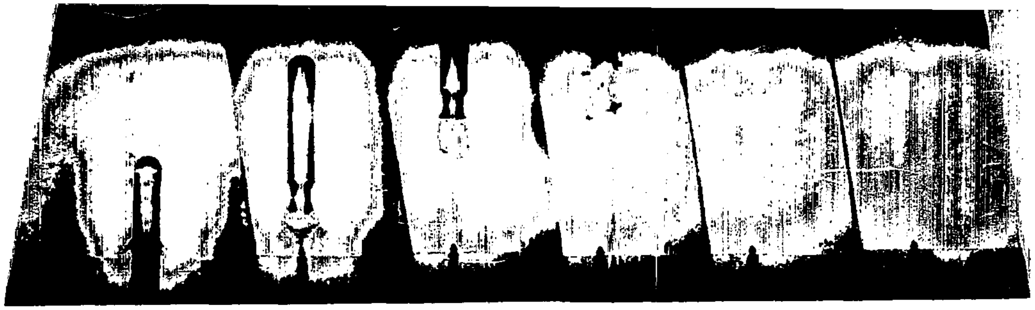
2



Time from water exit, ms

(a) 1 atm pressure in tank

1



-22.5 -10.5 1.5 13.5 25.5 37.5

Time from water exit, ms

(a) 1 atm pressure in tank

-22.7 -10.7 1.3 13.3 25.3 37.3

Time from water exit, ms

(b) 0.75 atm pressure in tank

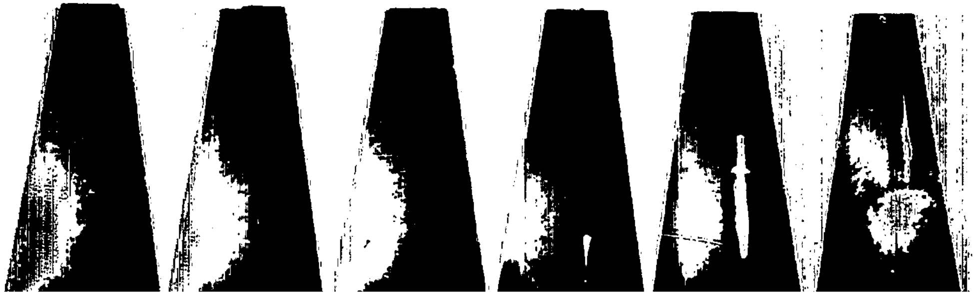
FIG. 12. Water Exit of Missile Without Probe Launched Vertically. Nominal water-exit velocity 60 fps.

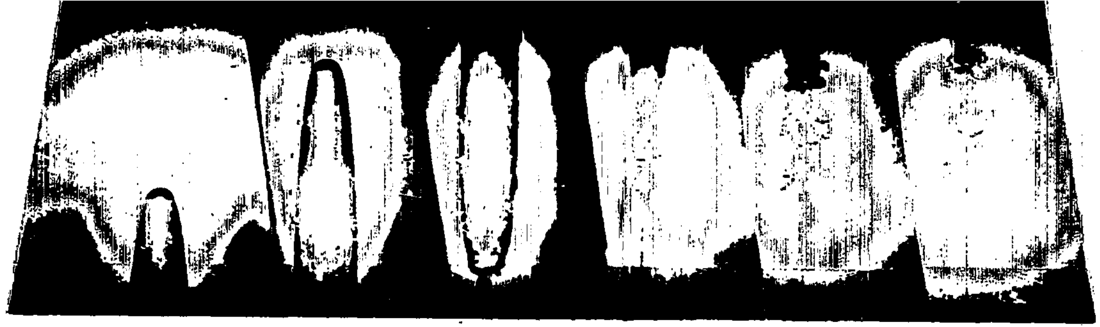
2

-23.5 -11.5 0.5 12.5 24.5 36.5

Time from water exit, ms

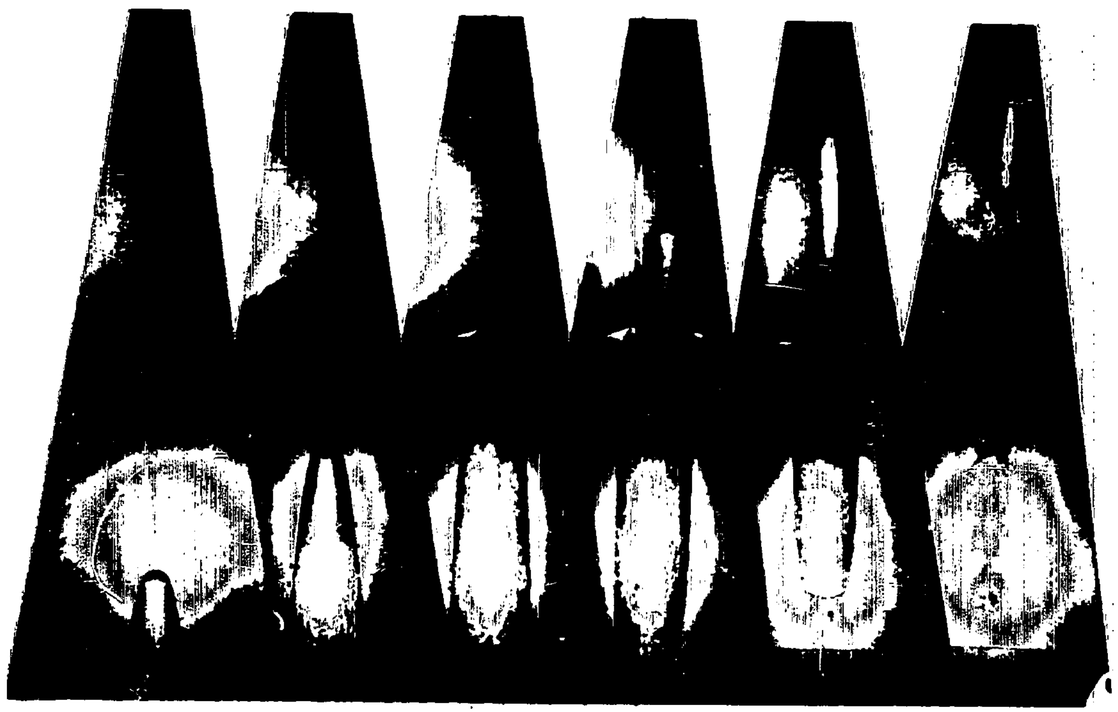
(c) 0.50 atm pressure in tank





Time from water exit, ms

(d) 0.20 atm pressure in tank



Time from water exit, ms

(e) 0.10 atm pressure in tank

FIG. 12. (Contd.)

2

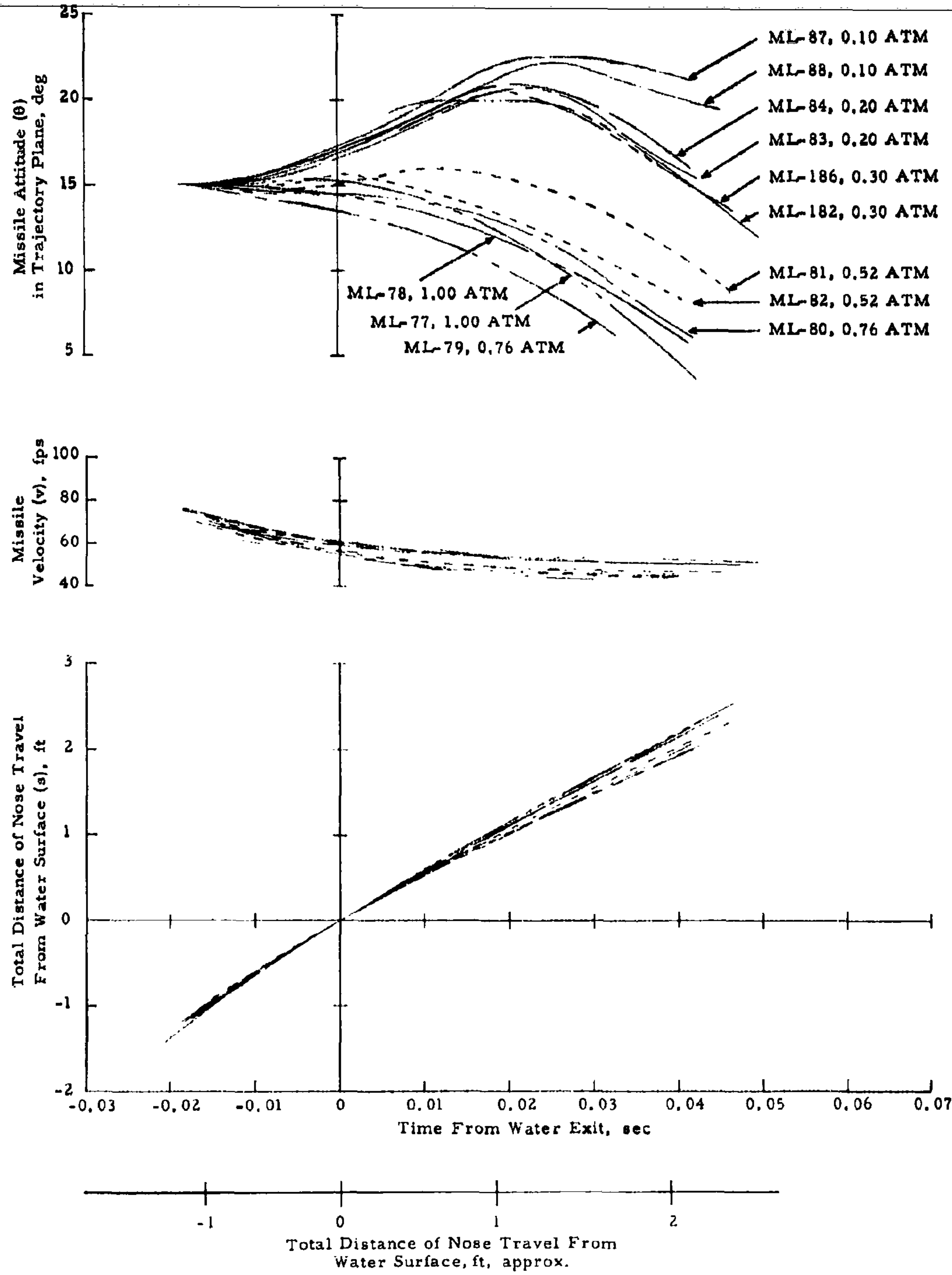


FIG. 13. Effect of Atmospheric Pressure on Water-Exit Behavior of Missile Without Probe Launched at 15-deg Angle.

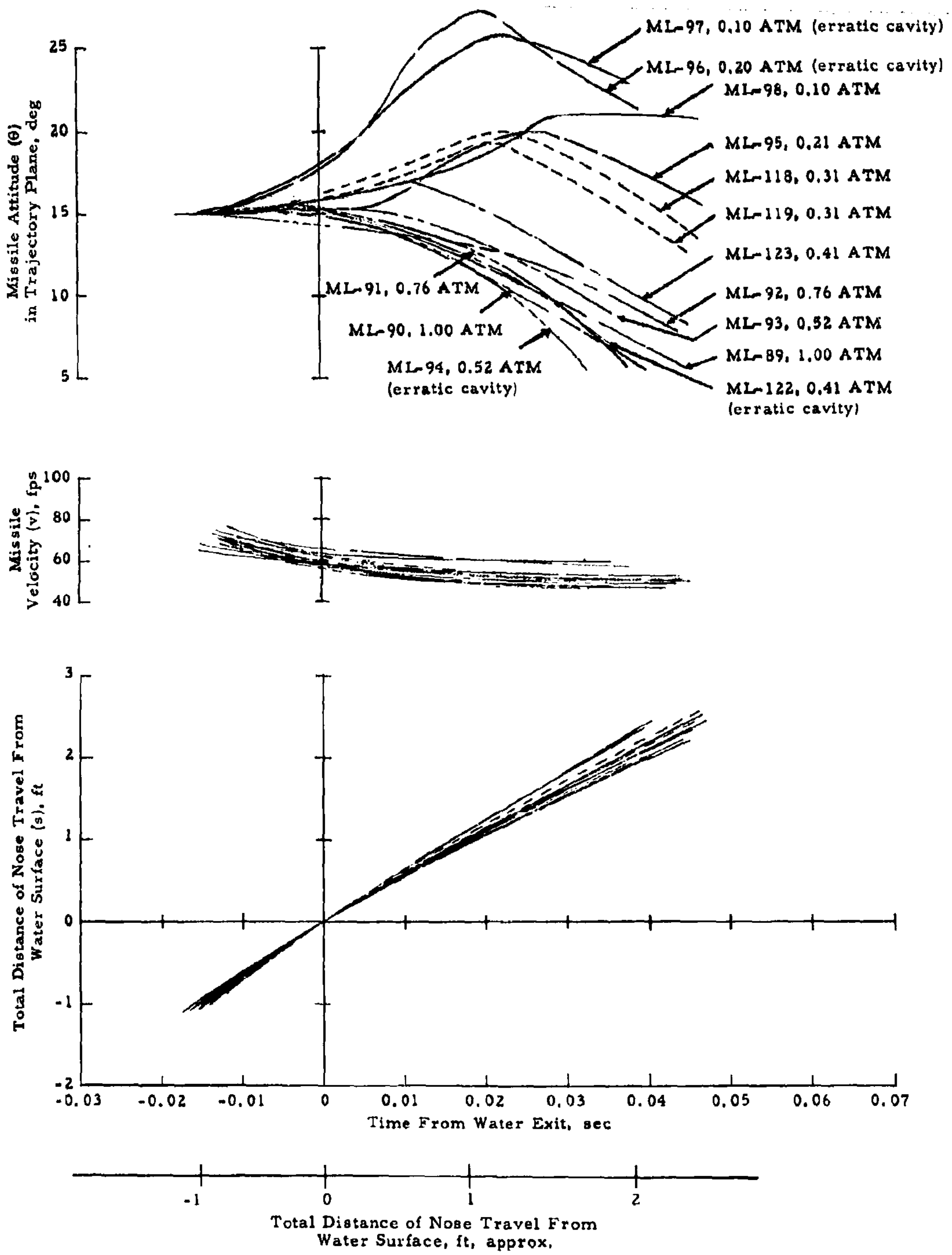


FIG. 14. Effect of Atmospheric Pressure on Water-Exit Behavior of Missile With Probe Launched at 15-deg Angle.

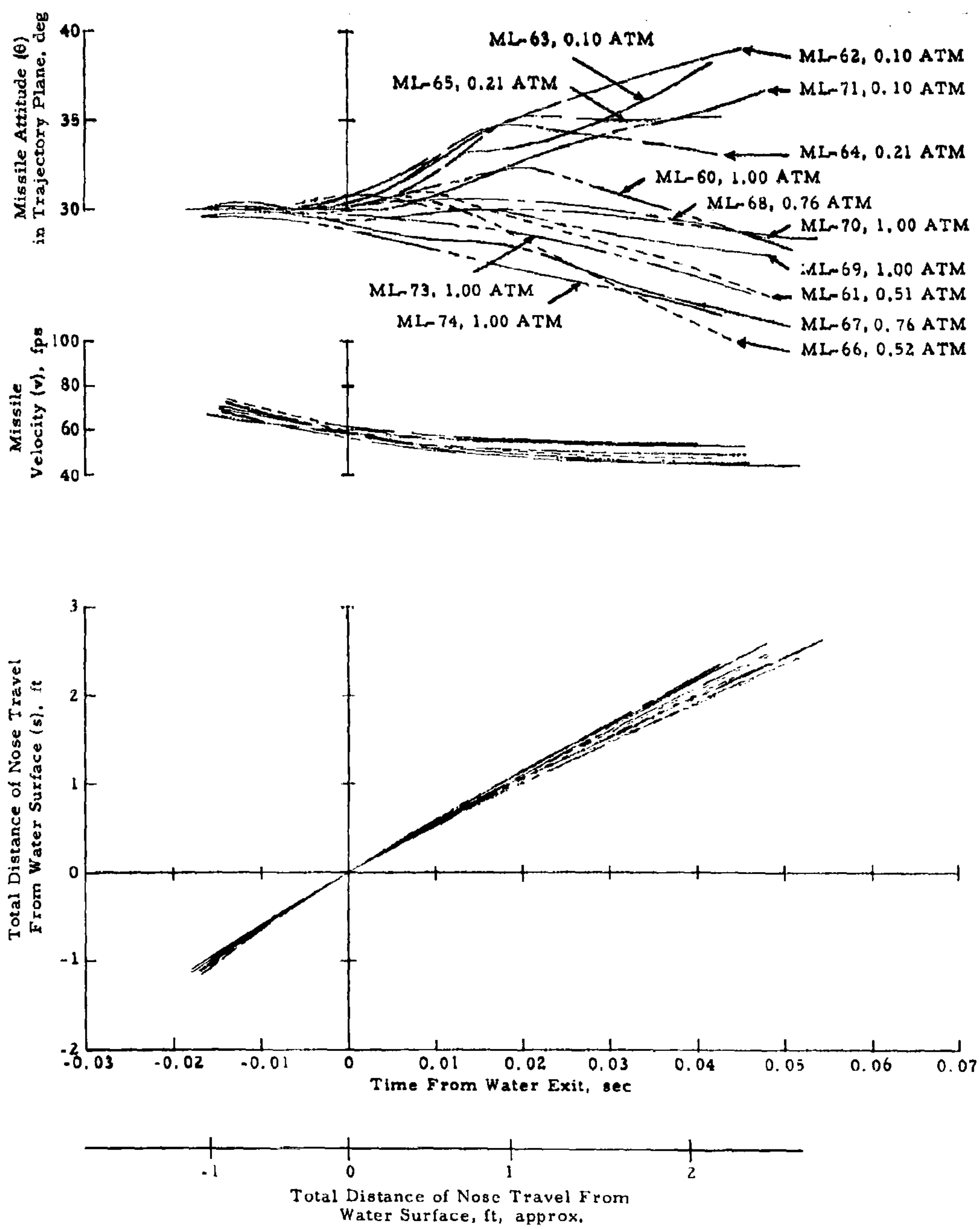


FIG. 15. Effect of Atmospheric Pressure on Water-Exit Behavior of Missile Without Probe Launched at 30-deg Angle.

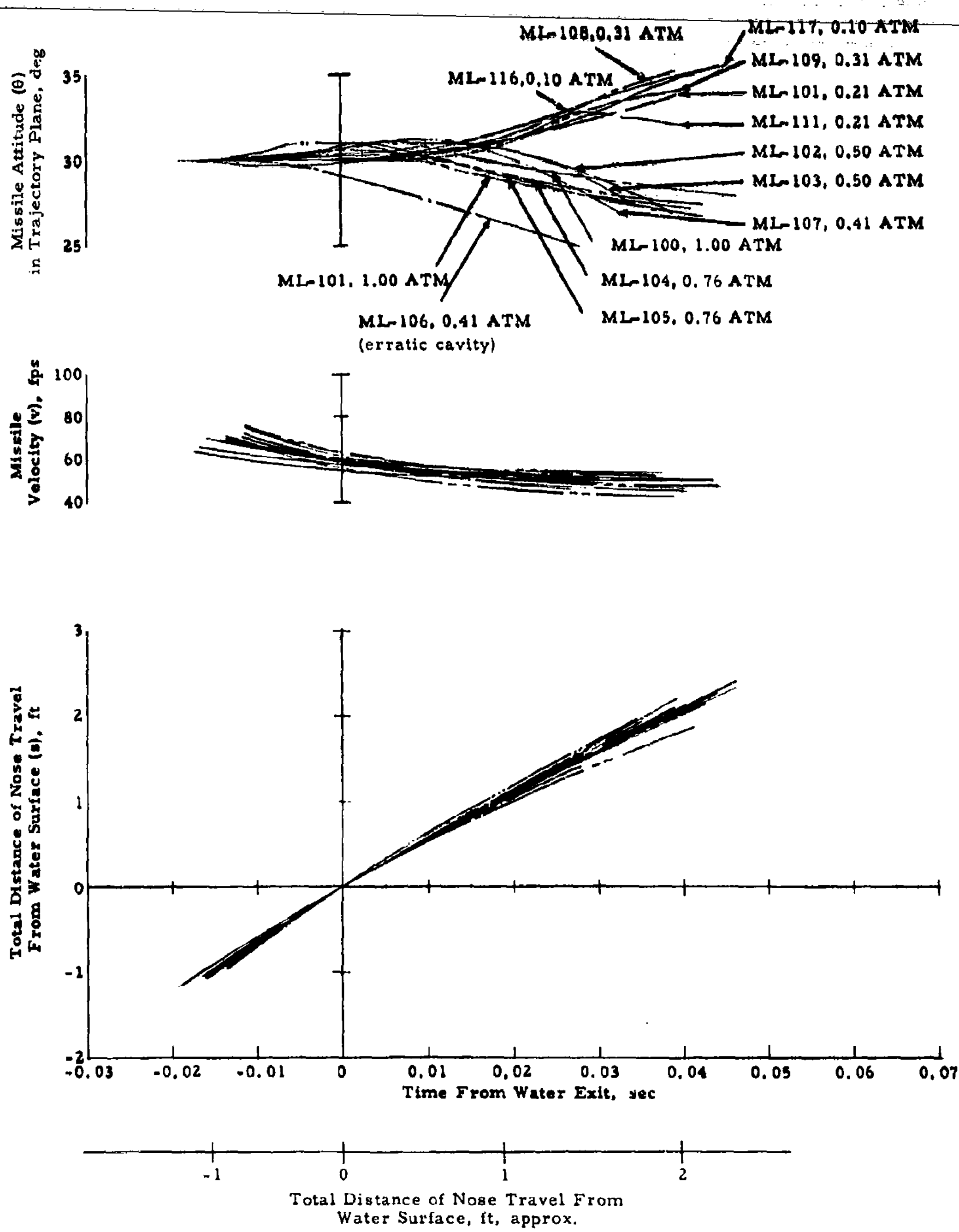


FIG. 16. Effect of Atmospheric Pressure on Water-Exit Behavior of Missile With Probe Launched at 30-deg Angle.

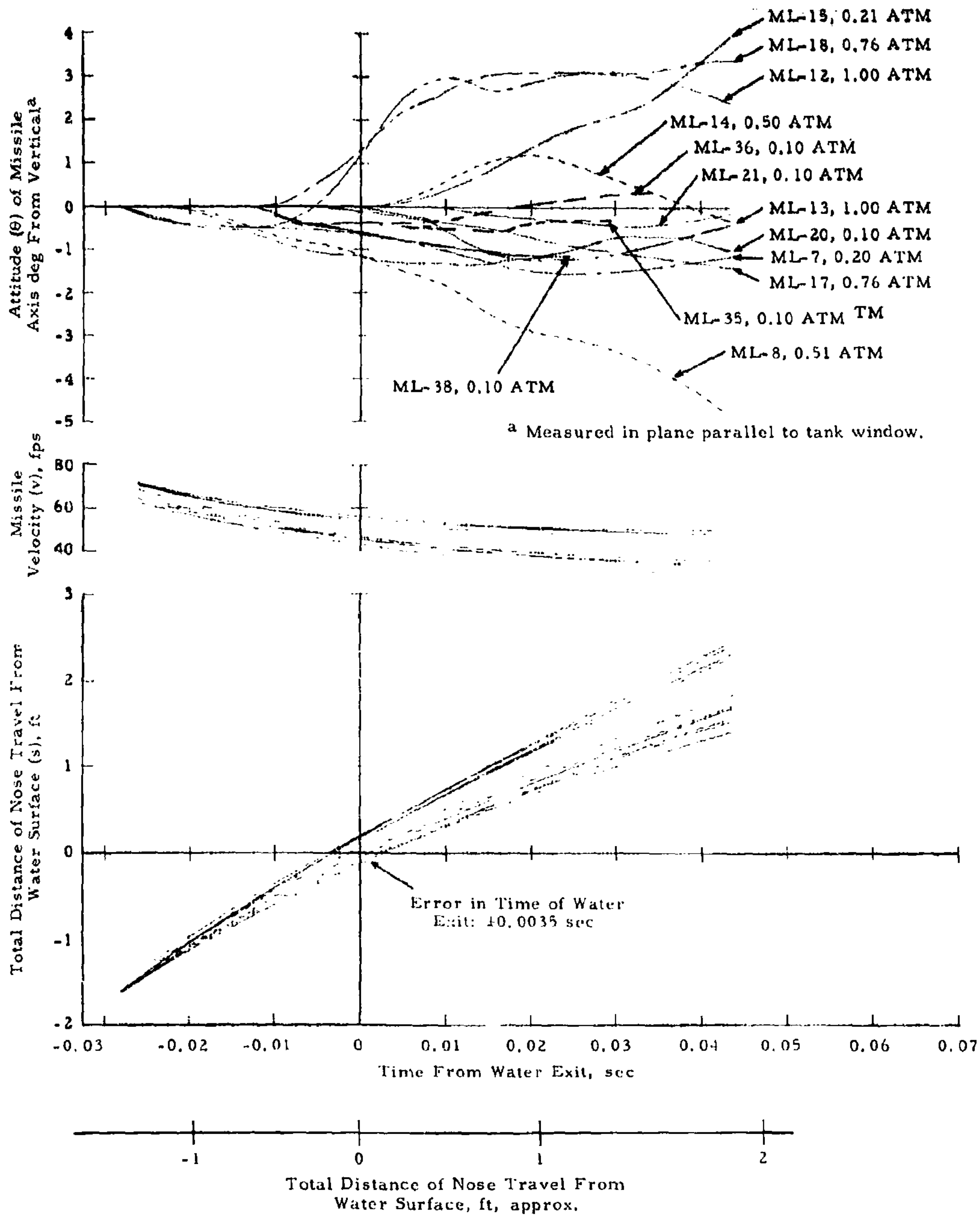


FIG. 17. Effect of Atmospheric Pressure on Water-Exit Behavior of Missile Without Probe Launched Vertically.

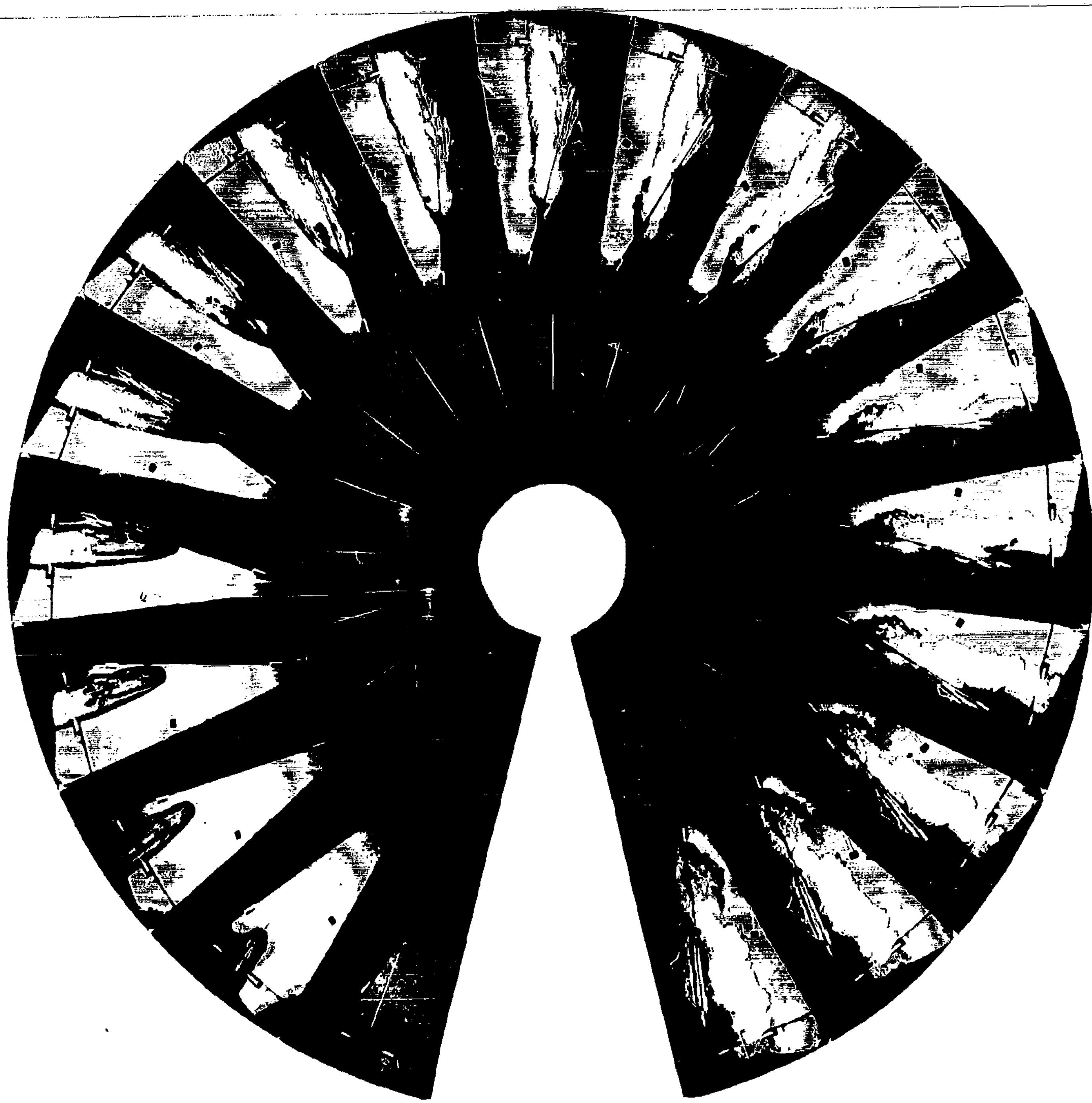


FIG. 18. Erratic Cavity Caused by Addition of Probe to Missile. (ML 97, velocity 63.3 fps, pressure 0.1 atm.)

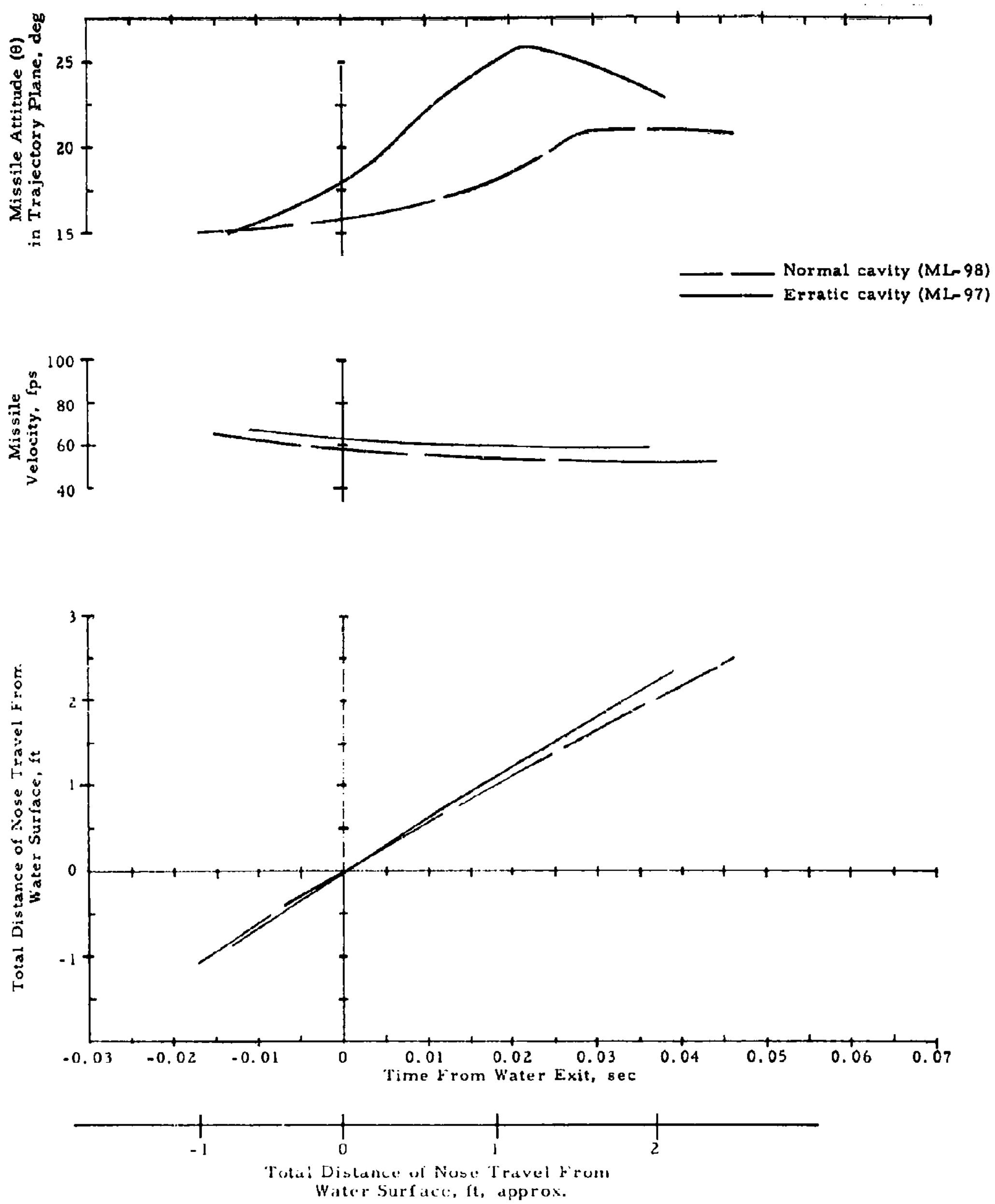


FIG. 19. Effect of Normal and Erratic Cavities Upon Missile Behavior.

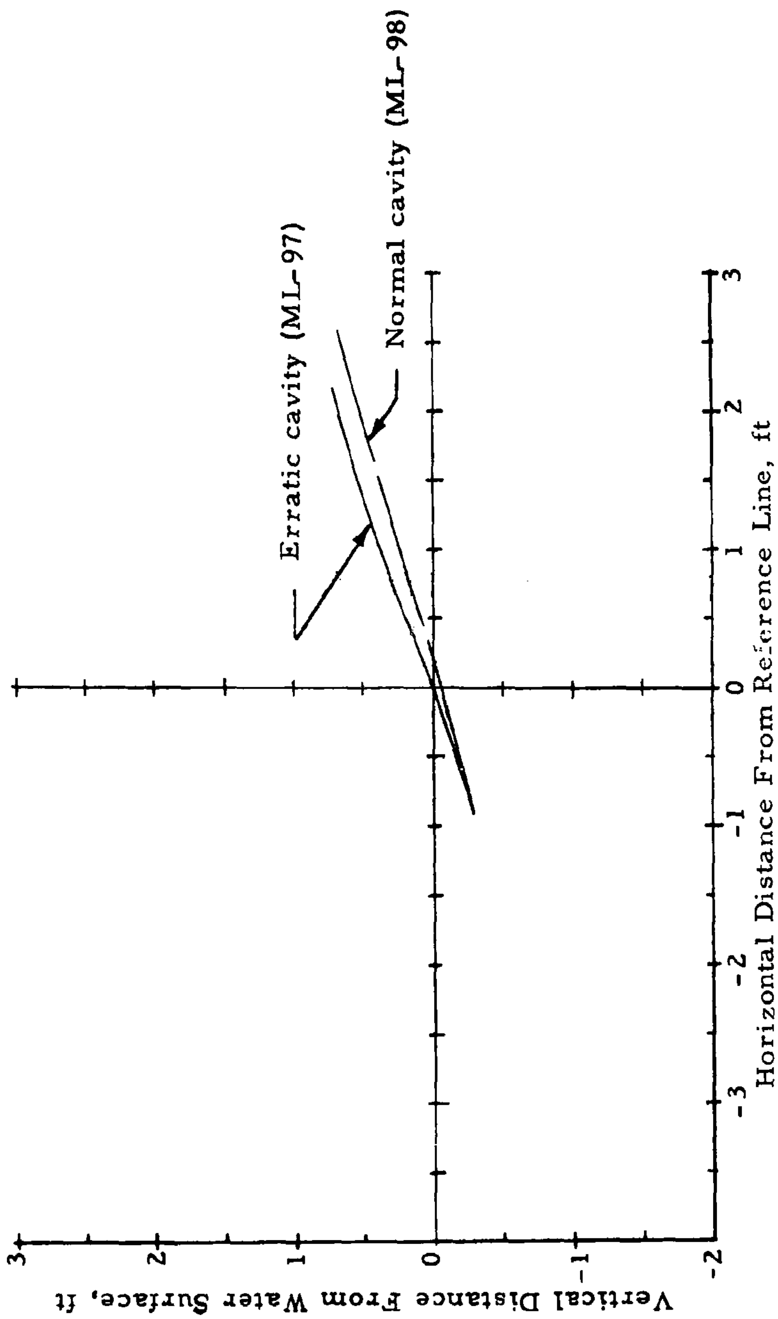


FIG. 20. Effect of Normal and Erratic Cavities Upon Missile Trajectories.

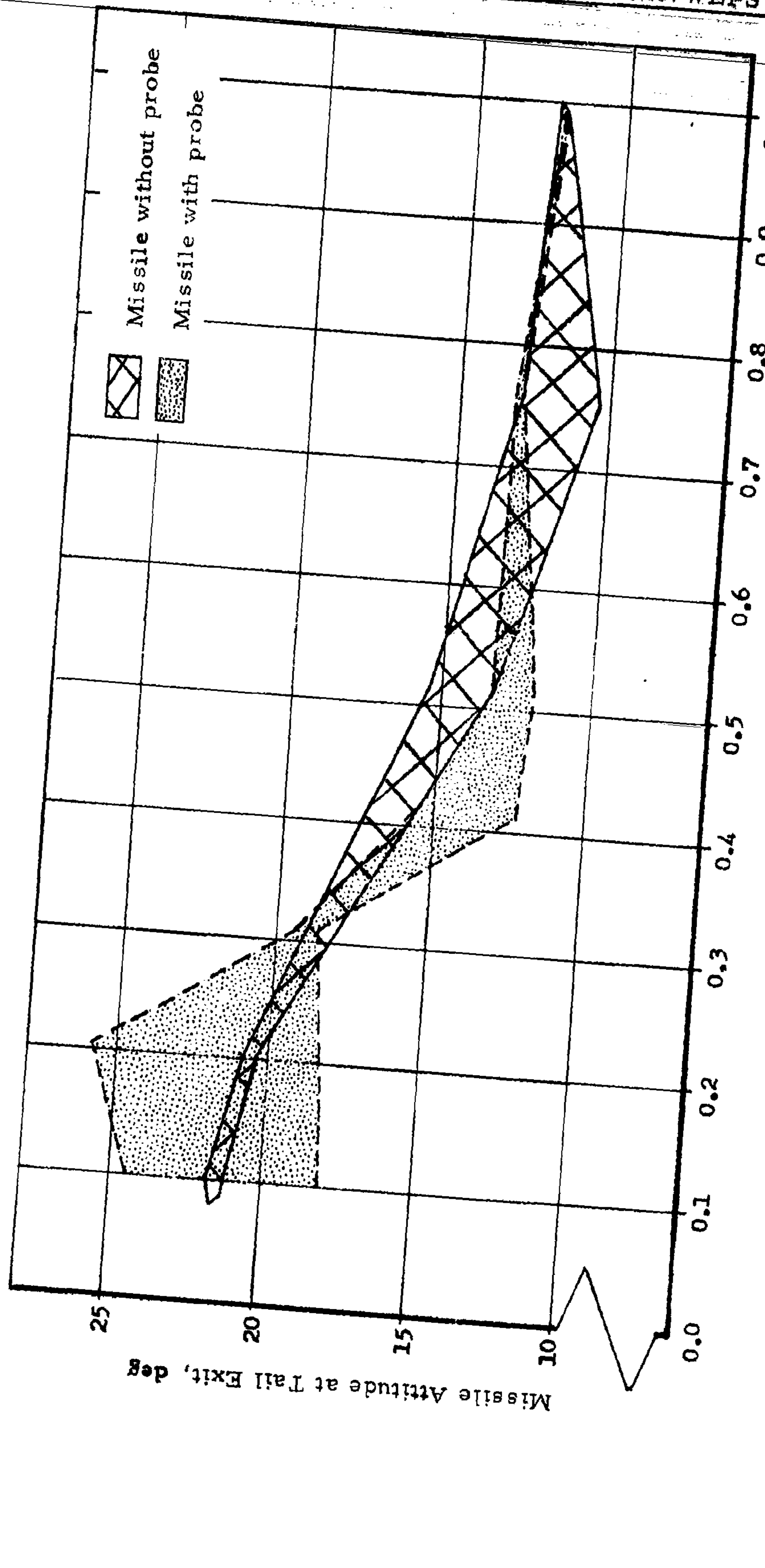


FIG. 21. Effect of Atmospheric Pressure on Missile Attitude at Tail Exit, Missile Launched at 15 deg

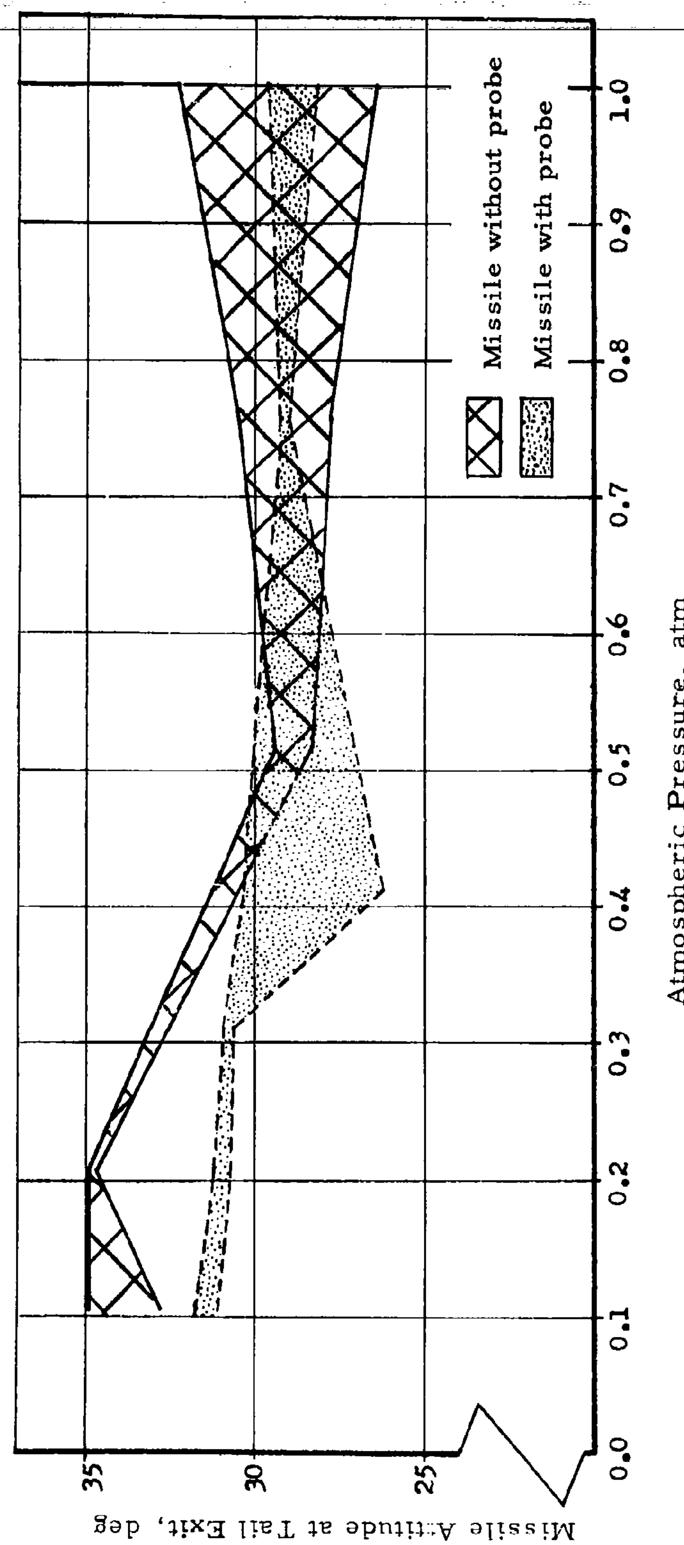


FIG. 22. Effect of Atmospheric Pressure on Missile Attitude at Tail Exit; Missile Launched at 30 deg.

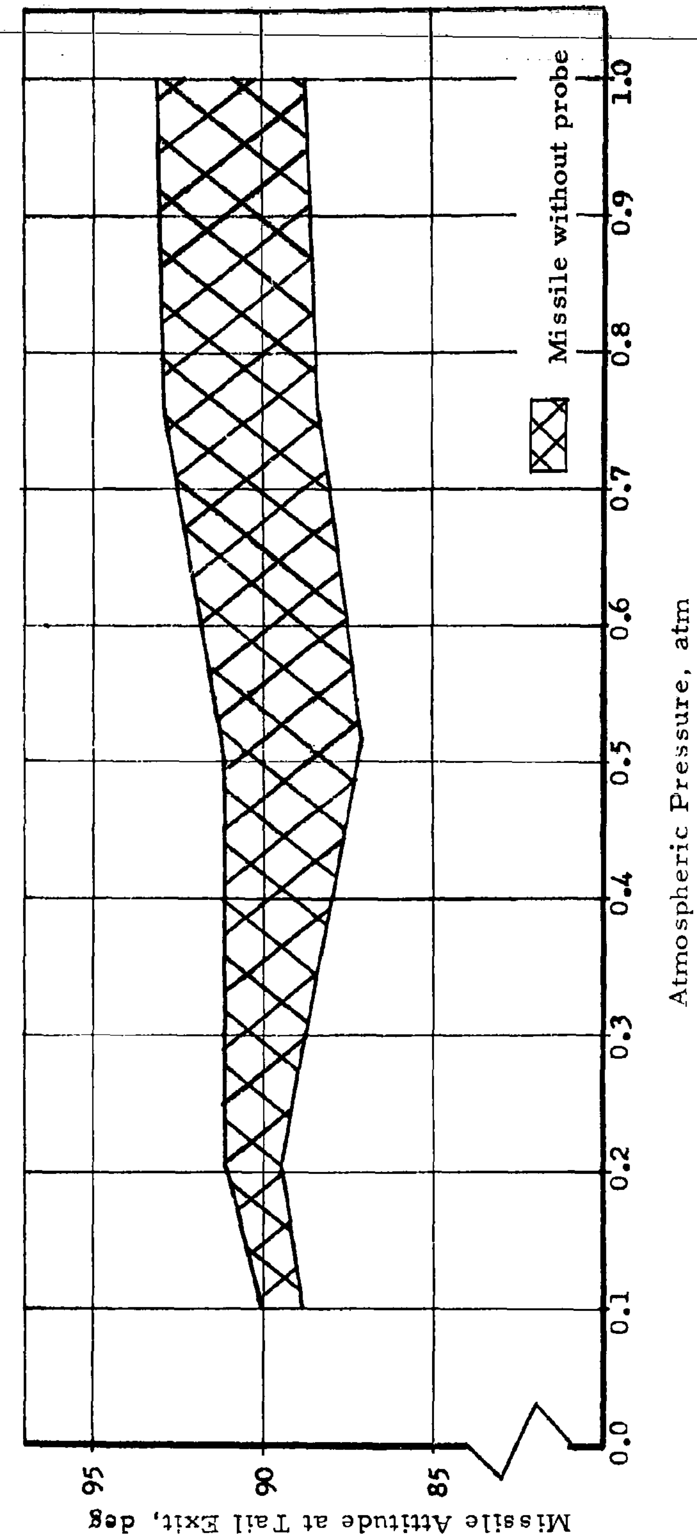


FIG. 23. Effect of Atmospheric Pressure on Missile Attitude at Tail Exit; Missile Launched Vertically.

modeling (i. e., gas density, etc) were not scaled during these tests. However, it is not unreasonable to assume that perturbations of comparable magnitude will exist during the water exit of prototype missiles.

For those who wish to use these data for making qualitative predictions of prototype missile behavior on the premise that modeling will obtain with one-to-one Froude and cavitation-number scaling, the following model-prototype relationships may be used (Ref. 4 and 5).

$$\lambda = d_m / d_p \tag{1}$$

$$\ell_m = \lambda \ell_p \tag{2}$$

$$m_m = \lambda^3 m_p \tag{3}$$

$$I_m = \lambda^5 I_p \tag{4}$$

$$p_{gm} = \lambda p_{gp} \tag{5}$$

$$s_m = \lambda s_p \tag{6}$$

$$t_m(s_m) = \sqrt{\lambda}\, t_p(s_p) \tag{7}$$

$$s_m(t_m) = \lambda s_p(t_p) \tag{8}$$

$$v_m(t_m) = \sqrt{\lambda}\, v_p(t_p) \tag{9}$$

$$\theta_m(t_m) = \theta_p(t_p) \tag{10}$$

$$\sqrt{\lambda}\, \dot{\theta}_m(t_m) = \dot{\theta}_p(t_p) \tag{11}$$

Since prototype missiles will be launched with 1 atmosphere air pressure over the water surface, p_{gp} = 1 atmosphere and λ will be fixed by the air pressure over the water surface, p_{gm}, of the particular model launchings considered. The prototype missile parameters and water-exit behavior can then be determined.

PROBE STUDIES

It was desirable to develop a technique for obtaining consistent behavior with a probe in the missile nose without modifying the head configuration. Consequently, a study of missile and cavity behavior and flow over the missile nose was made, using various probe configurations and launching conditions (Tables 7 and 8). All launchings were made at a 15-degree trajectory angle, where previous tests had shown inconsistent missile behavior likely to occur.

Since variation in missile-surface condition could be responsible for erratic cavities (Ref. 6), two uniform missile-surface conditions were considered for study: a perfectly clean hydrophilic surface to

TABLE 7. Description of Probes Used for Special Probe Studies

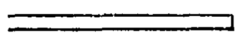
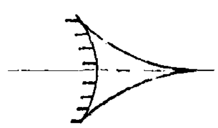
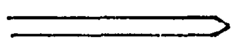
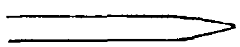
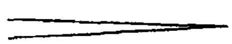
	A.	Standard probe. Cylindrical flat head probe as originally used (Fig. 1) but degreased.
	B.	Similar to type A except hollowed to hold dye paste.
	C.	Similar to type A except coated with dye paste.
	D.	Nylon fairing probe.
	E.	Cylindrical probe with 60-degree included angle cone head.
	F.	Similar to type E except slotted to hold dye paste.
	G.	Conical probe tapered to a point with slight convex curvature (pseudo-Lyons form).
	H.	Similar to type G except coated with dye paste.
	I.	Conical probe.
	J.	Similar to type I except coated with dye paste.
	K.	Similar to type A except that a groove was cut into the missile nose (Fig. 26).

TABLE 8. Water-Exit Launching Data

Hemisphere head missile with special probes. Trajectory launching angle: 15 degrees.

ML No.	Air Pressure in Tank, atm	Initial Pitch θ_o, deg	v_e, fps	F	σ	ρ'	τ	Type of Probe[a]
135	0.10	15.3	56.9	24.6	0.050	0.10	458.6	A
136[b]	0.10	15.0	...	...	...	...	...	A
137[b]	0.10	15.0	...	...	...	...	...	A
139[b]	0.10	15.0	...	...	...	...	...	A
148[b,c,e]	0.20	15.0	...	...	...	...	...	B
147[b,e]	0.20	15.0	...	...	...	...	...	C
168[b,c]	0.10	15.0	...	...	...	...	...	D
169[b,c]	0.10	15.0	...	...	...	...	...	D
134	0.10	15.7	63.1	27.2	0.041	0.10	508.6	E
151[b,c]	0.20	15.0	...	...	...	...	...	E
153[b,c]	0.20	15.0	...	...	...	...	...	E
162[b,c]	0.20	15.0	...	...	...	...	...	F
140	0.10	16.7	62.7	27.1	0.041	0.10	505.6	G
141[b]	0.10	15.0	...	...	...	...	...	G
142[b]	0.10	15.0	...	...	...	...	...	G
165[b,c]	0.20	15.0	...	...	...	...	...	H
149[b,c]	0.20	15.0	...	...	...	...	...	I
150[b,c]	0.20	15.0	...	...	...	...	...	I
166[b,c]	0.20	15.0	...	...	...	...	...	J
172[b,c]	0.10	15.0	...	...	...	...	...	A[d]
173[b,c]	0.10	15.0	...	...	...	...	...	A[d]
175	0.10	15.0	56.5	24.4	0.047	0.10	728.5	A[d]
176	0.10	15.0	55.9	24.1	0.048	0.10	720.7	A[d]
188[b]	0.10	15.0	...	...	...	...	...	K
189[b]	0.10	15.0	...	...	...	...	...	K
190	0.10	15.7	58.5	25.3	0.046	0.10	472.1	K
191	0.10	15.1	58.5	25.3	0.046	0.10	472.1	K
192	0.10	15.0	57.0	24.6	0.049	0.10	459.1	K
193	0.10	15.7	58.5	25.3	0.046	0.10	472.3	K

[a] Table 7 gives details of probe.
[b] Used for visual observations only.
[c] Photographed at 1,000 frames per second.
[d] Similar to type A probe but length = 1.27 ± 0.03 inches. Water in tank contained aerosol.
[e] Trial launching made to develop dye technique.

suppress cavitation, and a uniformly greasy hydrophobic surface to aid cavitation. The production of perfectly clean surfaces is inconsistent with the conditions under which models and full-scale missiles are tested. Therefore it was decided to maintain a uniformly hydrophobic surface, which can be obtained by handling the missile to coat its surface with oil from the skin (Ref. 7). Four launchings were made with the missile and standard probe carefully degreased and then regreased by handling just prior to launching. Although this technique did not prevent the formation of erratic cavities, it was retained as a precaution in all subsequent water-exit launchings.

It appeared possible that reduction of water-surface tension might prevent or decrease erratic cavity formation because this did eliminate stripping of the water-entry cavities formed by a spherogive-head missile (Ref. 8). Thus four launchings were made with the standard probe in water whose surface tension was reduced to approximately 28.4 dynes/cm by the addition of less than 0.1 percent by weight of Aerosol OT (Ref. 9) to the water. Reducing the surface tension increased the incidence of erratic cavities.

Three probe configurations were studied in addition to the standard one: a cylinder with cone head of 60 degrees included angle, a quasi-cone with slight convex curvature, and a cone. Reducing the bluntness of the probe also increased the incidence of erratic cavities.

The flow over the missile nose was made visible with nigrosine dye, the paste being used to fill slots in the probes. In the case of the standard probe a slotted tube of the same external dimensions was used instead of a rod. During the launching and subsequent underwater trajectory the dye streamed from the slot, marking the flow along the probe and over the missile nose. Minute vortices were visible in the dye trace and a zone of separation seemed to occur at the base of the probe (Fig. 24). Fairing the probe to fill the approximate zone of separation improved the cavity significantly (Fig. 25), and indicated that the erratic cavity formation was being caused by disturbances in the flow introduced by separation of the probe boundary layer. Using a fairing to eliminate erratic cavities is not feasible because it is impossible to match the zone of separation over the entire trajectory. Moreover, a fairing would defeat the original purpose of the probe, namely, to obtain accurate missile attitude data.

These studies indicated that it would be necessary to mask any random perturbation introduced by the probe boundary layer, and force regular separation of the cavity in the proper separation zone. In order to accomplish this, some modification such as roughening or grooving the missile nose was necessary. It was decided to cut an annular groove in the nose where the cavity would normally tend to separate, i.e., where the hemisphere subtends an angle of about 78 degrees (Fig. 26). More than 100 water-exit launchings of the missile with grooved head and standard probe indicate that the technique is successful in eliminating erratic cavities, but randomness in missile perturbation still persisted. These launchings will be discussed in a subsequent part of this report.

CONCLUSIONS

Water-exit launchings were made with a 2-inch-diameter hemisphere-head missile at 60-fps nominal water-exit velocity, launching angles of 15, 30, and 90 degrees with respect to the horizontal, and different degrees of cavitation ranging from nearly fully wetted flow to completely enveloping cavitation. The following conclusions are drawn:

1. The missile is perturbed at water exit under all degrees of cavitation. The perturbations increase with decrease in trajectory angle, the maximum perturbations occurring under conditions of fully developed cavitation. From these results it is inferred that water-exit perturbations will pose problems in service-missile water-exit technology.

2. The addition of a nose probe alters the water-exit perturbations of the missile and sometimes causes erratic cavities to form. An annular groove cut in the missile nose at the zone of cavity separation stabilized the cavity but did not prevent random perturbations from occurring.

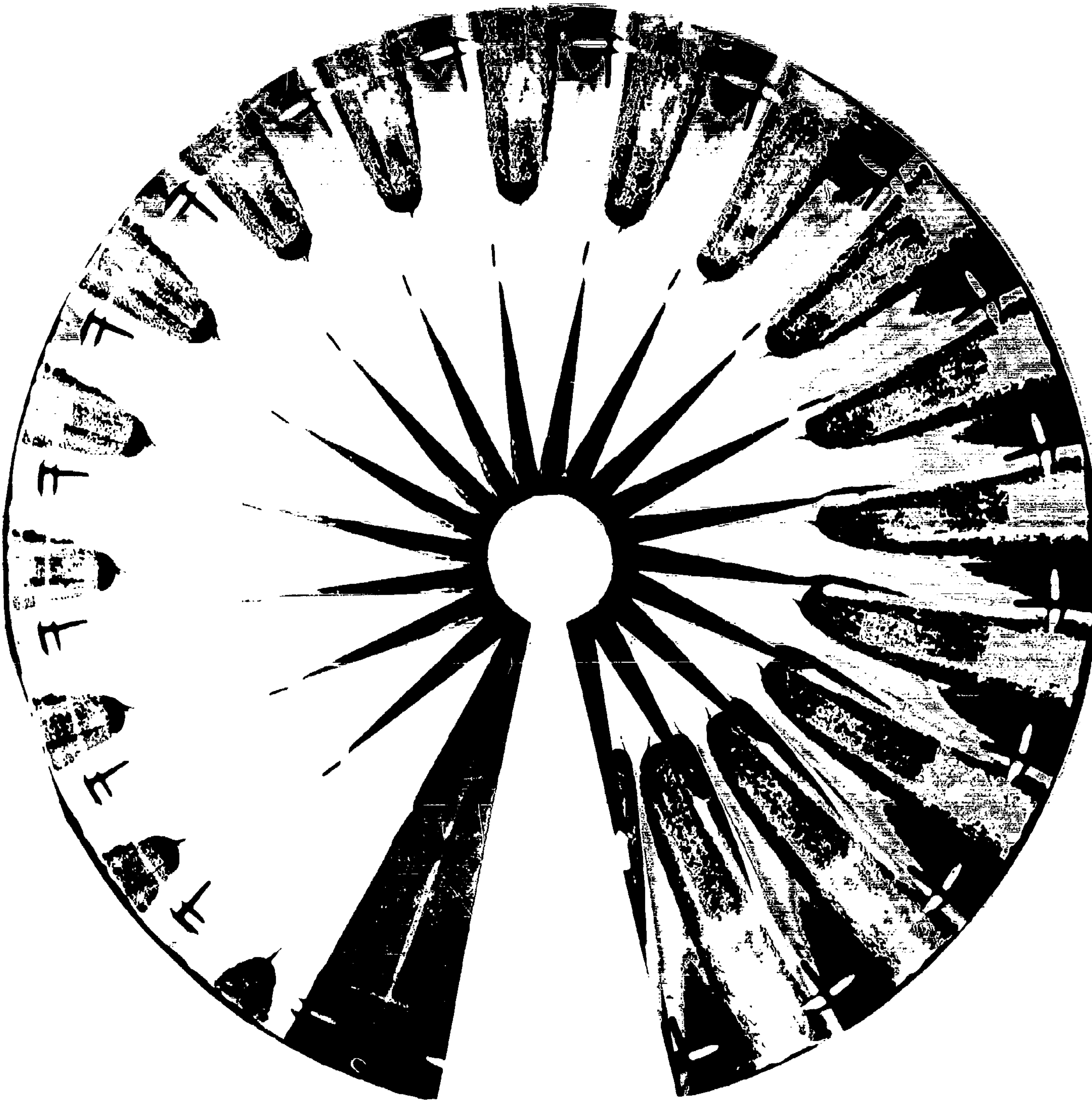


FIG. 24. Dye Trace From Slotted Probe Marking Large Zone of Separation on Missile Nose. (ML 148.)

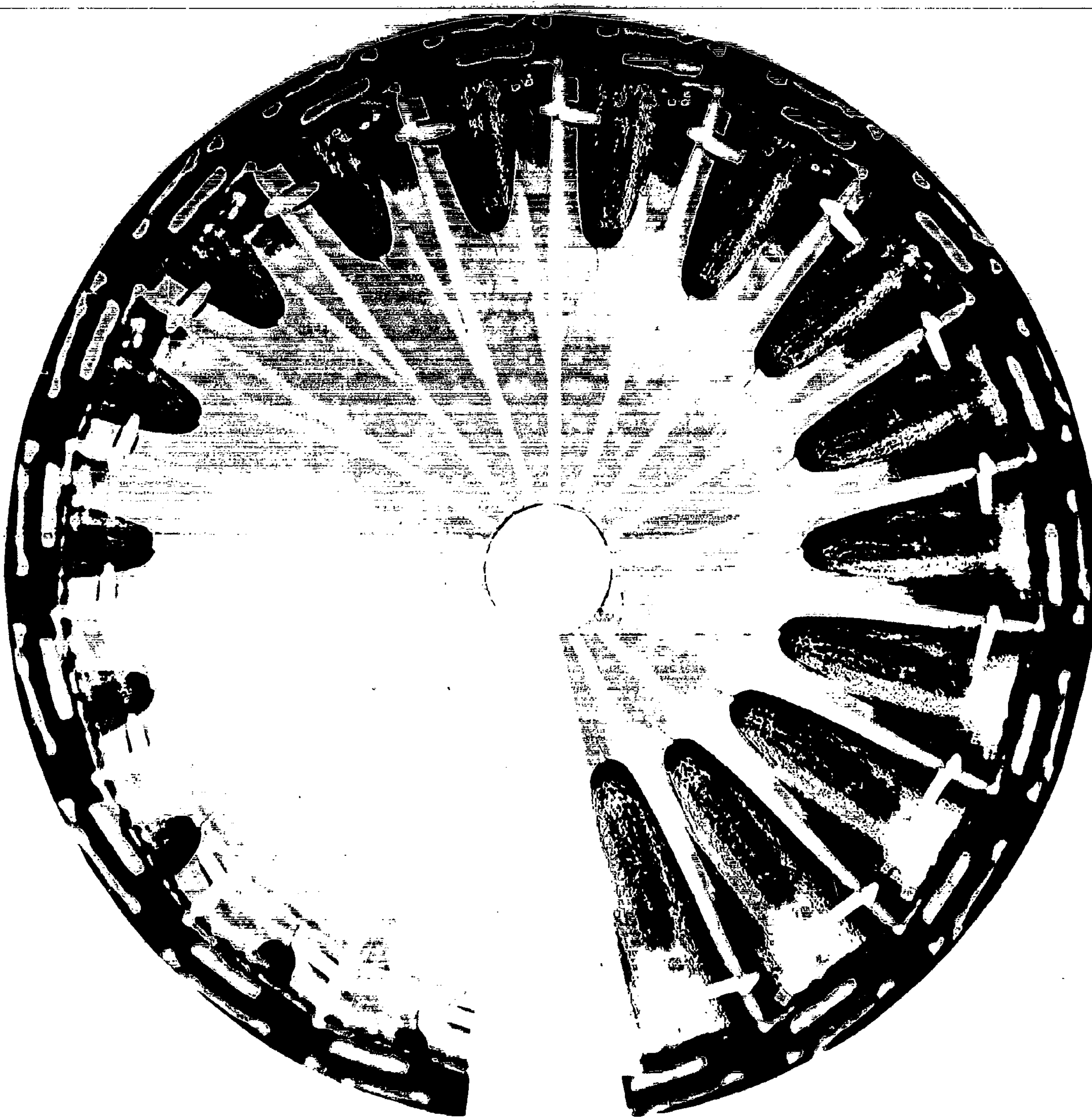


FIG. 25. Stabilization of Cavity by Nylon Fairing on Missile Nose. (ML 168.)

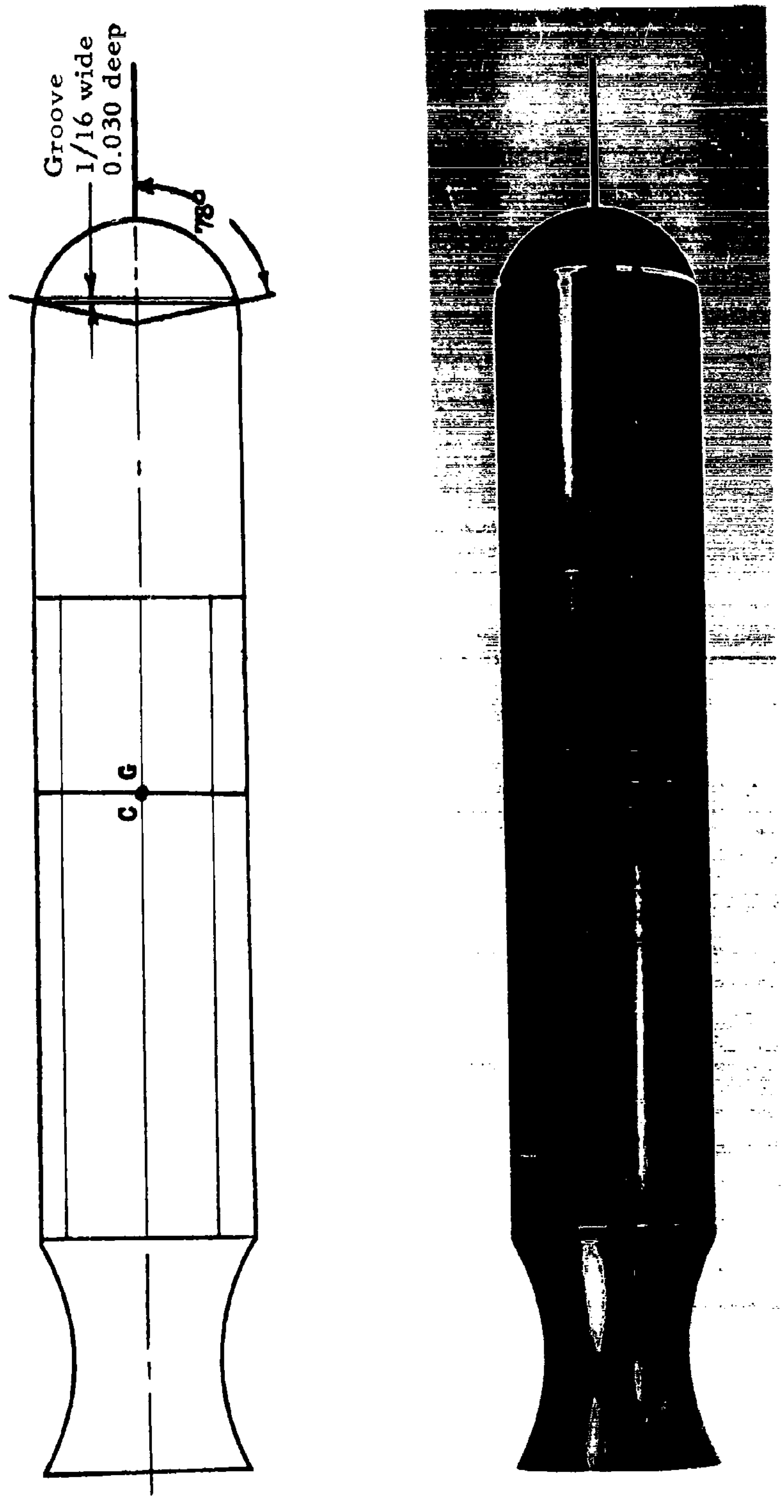


FIG. 26. Missile With Grooved Head. Dimensions as shown in Fig. 1.

NOMENCLATURE

d	Diameter of missile body, in.
F	Froude number at water exit, $F = v_e/\sqrt{dg}$
g	Acceleration of gravity, ft sec^{-2}
I	Moment of inertia of missile about any transverse axis through the CG, lb in^2
ℓ	Distance from nose to CG of missile, in.
m	Mass of missile, lb
p_c	Sum of the gas and vapor pressures in the cavitation bubble acting to keep the bubble open, lb ft^{-2} or atmospheres
p_g	Atmospheric pressure, lb ft^{-2} or atmospheres (standard atmospheric pressure = 740-mm mercury pressure)
R	Reynolds number, $R = vd/\nu$
s	Missile water penetration measured along trajectory from point of water exit, ft
S	Surface tension of water, dynes cm^{-1}
t	Time from instant of missile water exit, sec
v	Velocity of missile, ft sec^{-1}
θ	Missile attitude in trajectory plane and measured with respect to horizontal, positive in the sense of nose-up rotation
θ_o	Attitude of missile measured when foremost point of missile nose is 6 in. from point of surface penetration
λ	Modeling scale factor, $\lambda = d_m/d_p$
ν	Kinematic viscosity, ft^2 sec^{-1}
ξ	Trajectory angle of missile, deg. Path angle with respect to horizontal plane, positive in climb
ρ'	Ratio of the density of the gas at the temperature and pressure of the tank atmosphere to that of dry air at 20°C and 740-mm Hg pressure
ρ_g	Density of gas, slug ft^{-3}
ρ_w	Density of water, slug ft^{-3}

σ Cavitation number at water surface, $\sigma = (p_g - p_c)/\frac{1}{2}\rho_w v^2{}_e$

τ Weber number, $\tau = v/\sqrt{S/\rho_w d}$

SUBSCRIPTS

e Water-exit condition

m Model missiles

p Prototype missiles

REFERENCES

1. U. S. Navy Bureau of Ordnance. Hydroballistics Design Handbook, Chapter 12. Washington 25, D. C., March 1955. (NAVORD Report 3533), CONFIDENTIAL.

2. U. S. Naval Ordnance Test Station, Inyokern. Variable Atmosphere Interface Model Launching Facility. Article published in Activities of the Underwater Ordnance Department. China Lake, Calif., NOTS, June 1951, CONFIDENTIAL.

3. Goldstein, S. Modern Developments in Fluid Dynamics. Oxford, Clarendon Press, 1950.

4. Office of Scientific Research and Development. Mathematical Studies Relating to Military Physical Research, Washington, OSRD, Columbia University, 1946. (Summary technical report of the Applied Mathematics Panel, NDRC, Vol. 1.)

5. Birkhoff, Garrett. Hydrodynamics. Princeton, N. J., Princeton University Press, 1950.

6. Worthington, A. M. A Study of Splashes. Longmans, Green and Company, London, 1908.

7. May, Albert. Effect of Surface Condition of a Sphere on Its Water-Entry Cavity, J APPL PHYS, Vol. 22 (Oct. 1951), pp. 1219-22.

8. California Institute of Technology. Water Entry Study of the Mk 25 Torpedo With 3.5-Calibre 70-Degree Spherogive Head, by G. M. Wilcox and J. G. Waugh. Pasadena, Calif., CIT, May 1953. (Hydrodynamics Laboratory Report No. E-12.12.), CONFIDENTIAL.

9. American Cyanamid Company, Aerosol Wetting Agents. New York, N. Y., 1946.

INITIAL DISTRIBUTION

20 Chief, Bureau of Naval Weapons
  DLI-31 (2)
  RRRE (1)
  RRRE-7 (1)
  RRRE-71 (12)
  RU (1)
  RU-12 (1)
  RUTO (1)
  RUTO-32 (1)
1 Chief of Naval Research (Code 438, Ralph Cooper)
1 David W. Taylor Model Basin
1 Naval Air Development Center, Johnsville
2 Naval Ordnance Laboratory, White Oak
  Dr. A. May (1)
1 Naval Postgraduate School, Monterey (Library, Technical Reports Section)
2 Naval Research Laboratory
  Code 5550 (1)
1 Naval Torpedo Station, Keyport (Quality Evaluation Laboratory, Technical Library)
1 Naval Underwater Ordnance Station, Newport
1 Naval Weapons Laboratory, Dahlgren
2 Naval Weapons Services Office, Naval Weapons Plant
1 Navy Electronics Laboratory, San Diego
1 Navy Underwater Sound Laboratory, Fort Trumbull
1 Office of Naval Research Branch Office, Pasadena
10 Armed Services Technical Information Agency (TIPCR)
1 Aerojet-General Corporation, Azusa, Calif., via BuWepsRep
1 Alden Hydraulic Laboratory, Worcester Polytechnic Institute, Worcester, Mass. (Prof. L. J. Harper)
1 Applied Physics Laboratory, University of Washington, Seattle
1 Convair Scientific Research Laboratory, San Diego (A. L. Berlad)
1 Davidson Laboratory, Stevens Institute of Technology, Hoboken, N. J.
1 Hudson Laboratories, Columbia University, Dobbs Ferry, N. Y.
2 Hydrodynamics Laboratory, CIT, Pasadena
  A. J. Acosta (1)
  Executive Committee (1)
1 Lockheed Aircraft Corporation, Missiles and Space Division, Palo Alto, Calif.

ABSTRACT CARD

U. S. Naval Ordnance Test Station
Water-Exit Behavior of Missiles. Part 1. Preliminary Studies, by J. G. Waugh and G. W. Stubstad. China Lake, Calif., NOTS, 11 May 1961. 54 pp. (NAVWEPS Report 7735, Part 1, NOTS TP 2693), UNCLASSIFIED.

(Over)
2 cards, 4 copies

U. S. Naval Ordnance Test Station
Water-Exit Behavior of Missiles. Part 1. Preliminary Studies, by J. G. Waugh and G. W. Stubstad. China Lake, Calif., NOTS, 11 May 1961. 54 pp. (NAVWEPS Report 7735, Part 1, NOTS TP 2693), UNCLASSIFIED.

(Over)
2 cards, 4 copies

U. S. Naval Ordnance Test Station
Water-Exit Behavior of Missiles. Part 1. Preliminary Studies, by J. G. Waugh and G. W. Stubstad. China Lake, Calif., NOTS, 11 May 1961. 54 pp. (NAVWEPS Report 7735, Part 1, NOTS TP 2693), UNCLASSIFIED.

(Over)
2 cards, 4 copies

U. S. Naval Ordnance Test Station
Water-Exit Behavior of Missiles. Part 1. Preliminary Studies, by J. G. Waugh and G. W. Stubstad. China Lake, Calif., NOTS, 11 May 1961. 54 pp. (NAVWEPS Report 7735, Part 1, NOTS TP 2693), UNCLASSIFIED.

(Over)
2 cards, 4 copies

NAVWEPS Report 7735
Part 1

ABSTRACT. Water-exit launchings were made with a 2-inch-diameter hemisphere-head missile at 60-fps nominal water-exit velocity; launching angles of 15, 30, and 90 degrees with respect to the horizontal; and different degrees of cavitation ranging from nearly fully wetted flow to completely enveloping cavitation. Perturbations in missile pitch at water exit increased with decrease in trajectory angle and the maximum perturbations occurred under conditions of fully developed cavitation. From the results it is inferred that water-

(Contd. on Card 2)

NAVWEPS Report 7735
Part 1

ABSTRACT. Water-exit launchings were made with a 2-inch-diameter hemisphere-head missile at 60-fps nominal water-exit velocity; launching angles of 15, 30, and 90 degrees with respect to the horizontal; and different degrees of cavitation ranging from nearly fully wetted flow to completely enveloping cavitation. Perturbations in missile pitch at water exit increased with decrease in trajectory angle and the maximum perturbations occurred under conditions of fully developed cavitation. From the results it is inferred that water-

(Contd. on Card 2)

NAVWEPS Report 7735
Part 1

ABSTRACT. Water-exit launchings were made with a 2-inch-diameter hemisphere-head missile at 60-fps nominal water-exit velocity; launching angles of 15, 30, and 90 degrees with respect to the horizontal; and different degrees of cavitation ranging from nearly fully wetted flow to completely enveloping cavitation. Perturbations in missile pitch at water exit increased with decrease in trajectory angle and the maximum perturbations occurred under conditions of fully developed cavitation. From the results it is inferred that water-

(Contd. on Card 2)

NAVWEPS Report 7735
Part 1

ABSTRACT. Water-exit launchings were made with a 2-inch-diameter hemisphere-head missile at 60-fps nominal water-exit velocity; launching angles of 15, 30, and 90 degrees with respect to the horizontal; and different degrees of cavitation ranging from nearly fully wetted flow to completely enveloping cavitation. Perturbations in missile pitch at water exit increased with decrease in trajectory angle and the maximum perturbations occurred under conditions of fully developed cavitation. From the results it is inferred that water-

(Contd. on Card 2)

ABSTRACT CARD

U. S. Naval Ordnance Test Station
Water-Exit Behavior of . . . (Card 2)
exit perturbations will pose problems in service missile water-exit technology.

The addition of a nose probe to measure cavitating missile attitudes altered the water-exit perturbations and sometimes caused erratic cavities to form. An annular groove in the missile nose at the zone of cavity separation stabilized the cavity and allowed more consistent results to be obtained.

NAVWEPS Report 7735
Part 1

U. S. Naval Ordnance Test Station
Water-Exit Behavior of . . . (Card 2)
exit perturbations will pose problems in service missile water-exit technology.

The addition of a nose probe to measure cavitating missile attitudes altered the water-exit perturbations and sometimes caused erratic cavities to form. An annular groove in the missile nose at the zone of cavity separation stabilized the cavity and allowed more consistent results to be obtained.

NAVWEPS Report 7735
Part 1

U. S. Naval Ordnance Test Station
Water-Exit Behavior of . . . (Card 2)
exit perturbations will pose problems in service missile water-exit technology.

The addition of a nose probe to measure cavitating missile attitudes altered the water-exit perturbations and sometimes caused erratic cavities to form. An annular groove in the missile nose at the zone of cavity separation stabilized the cavity and allowed more consistent results to be obtained.

NAVWEPS Report 7735
Part 1

U. S. Naval Ordnance Test Station
Water-Exit Behavior of . . . (Card 2)
exit perturbations will pose problems in service missile water-exit technology.

The addition of a nose probe to measure cavitating missile attitudes altered the water-exit perturbations and sometimes caused erratic cavities to form. An annular groove in the missile nose at the zone of cavity separation stabilized the cavity and allowed more consistent results to be obtained.

NAVWEPS Report 7735
Part 1